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12

THE DYNAMIC BEHAVIOR OF NYLON AND POLYESTER LINE

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16. Abstract

A series of tests were conducted to determine the dynamic response of nylon and polyester, double-braided and 8-strand plaited line. Line samples were excited mechanically in a tensile testing machine according to an experimental design in which frequency of excitation, mean load, and load amplitude were varied. The dynamic stiffness, called the apparent spring constant, was measured. Results indicate that the apparent spring constant is 3 to 4 times greater than the static elasticity.

Samples of nylon and polyester line were placed in the ocean for 4 to 5 years and then tested with the same dynamic test procedure as was previously performed on the new line samples. The apparent spring constant of nylon double-braided line approximately doubled after five years of exposure to the marine environment, and polyester 8-strand plaited and double-braided line increased about 10 to 25 percent. The increase in dynamic stiffness with age will result in an increase in tension for a given displacement.

Snap load tests were conducted on nylon 8-strand plaited line (snap load is a cyclic loading in which zero is the minimum tension) and it was found that samples failed from fatigue when the maximum load exceeds 30 percent of the rated breaking strength. Samples do not fail by 200,000 cycles if the maximum load does not exceed 30 percent.

Field and laboratory abrasion tests were also conducted on nylon, polyester, and polypropylene line of the 8-strand plaited, double-braided, and 3-strand twisted constructions. Some samples were jacketed with polyurethane and the abrasion resistance was increased by approximately 5 to 6 times.

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METRIC CONVERSION FACTORS

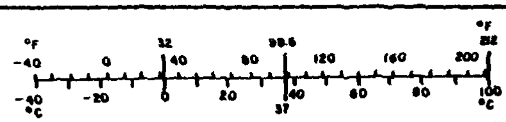
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

The U.S. Coast Guard Research and Development Center has undertaken a series of projects to investigate alternate buoys, moorings, and anchors for the aids to navigation system that the Coast Guard maintains. The work undertaken to investigate the physical properties of synthetic mooring materials is described in this report.

Synthetic mooring materials (here defined as nylon, polyester, and polypropylene) are considered as one alternative to the chain normally used on Coast Guard buoys. Among the attributes of synthetic mooring materials that might be attractive to the Coast Guard in some situations are energy absorption, lightweight, service life, and cost. The energy absorption mechanism of a synthetic mooring is quite different from that of a chain mooring. The conventional chain buoy mooring absorbs energy by virtue of the chain weight (i.e., catenary). As the buoy is moved by waves, the excess chain in the mooring is lifted off the ocean bottom and the energy is dissipated. The energy-dissipating capability of the chain mooring is greatly reduced after all the excess chain is lifted off the ocean bottom. This limits the amount by which the mooring designer can shorten the mooring in cases where less buoy excursion is desired.

In synthetic moorings energy is dissipated by elongation of the mooring material. Because of the low weight of synthetic moorings, little energy is absorbed by the catenary. The extensibility of synthetic mooring materials allows the mooring designer to shorten the mooring more than a corresponding chain mooring in situations where less buoy excursion is desirable. The energy-absorbing characteristics of synthetic moorings also have use in areas where high wave conditions have reduced the reliability of chain moorings as at some locations along the coast of Oregon and Washington.

The Coast Guard is placing buoys in water that is so deep that the buoy will sink under the weight of a chain mooring. In these situations, synthetic moorings are the only mooring method available.

The low weight of synthetic moorings is advantageous when used in conjunction with lightweight buoys and anchors. The entire buoy/mooring system can be deployed from a small boat in quick response to place a temporary buoy at the location normally occupied by a regular buoy if the regular buoy becomes inoperative.

The overall buoy/mooring development program included the investigation of shallow-water mooring dynamic computer programs. In order to evaluate a computer program effectively, realistic synthetic line properties must be obtained and used in the program. Without reliable parameters, it is difficult to determine how much of the program output error is attributed to the program's ability to model the physics of the mooring and how much is attributed to incorrect input data (i.e., synthetic line properties).

There is also a need to investigate other synthetic line properties that should be understood during the design of a synthetic mooring (e.g., abrasion resistance, snap load, etc.). To develop the information required to design synthetic moorings and use a computer program, a series of field and laboratory tests were conducted and are reported here.

So that this report will be of value to a diverse group of readers, it is organized in two general parts:

(a) First, a general discussion is presented of the most significant results of this investigation and its impact on the mooring designer. This information can be used directly by a mooring designer without the use of computer programs or other advanced techniques. The presentation is concise and does not include any detailed background, theory or experimental methods from which the results were drawn.

(b) In the second portion, the details of the individual experiments are presented from which the conclusions in the first part were drawn. Equations are given for calculating values of synthetic line properties such as the dynamic and quasi-static spring constants and the load-strain curves. The detailed results are documented for subsequent use in other work elements such as the development of a dynamic computer model of a buoy/synthetic mooring system.

2.0 SUMMARY

A series of tests were conducted to determine the dynamic response of nylon and polyester, double-braided and 8-strand plaited line. Line samples were excited mechanically in a Cyclic/Tensile Testing Machine according to an experimental design in which frequency of excitation, mean load, and load amplitude were varied. The dynamic stiffness, called the apparent spring constant, was measured. Results indicate that the apparent spring constant is 3 to 4 times greater than the static elasticity. Since the static elasticity is often used to characterize line even in a dynamic application, the actual dynamic load can be 3 to 4 times greater than the predicted load.

Samples of nylon and polyester line were placed in the ocean for 4 to 5 years and then tested with the same dynamic test procedure as was previously performed on the new line samples. The apparent spring constant of nylon double-braided line approximately doubled after five years of exposure to the marine environment, and polyester 8-strand plaited and double-braided line increased about 10 to 25%. These findings may eventually result in a step in the design procedure in which the response of the system will be checked using "old" line properties in a computer program to insure that the system can perform as it ages. The increase in dynamic stiffness with age will result in an increase in tension for a given displacement.

Both nylon and polyester lines lose approximately 50% of their original tensile strength after four/five years of exposure. The strain-at-failure increased approximately 50% in the same environment.

Snap load tests were conducted on nylon 8-strand plaited line (snap load is a cyclic loading in which zero is the minimum tension) and it was found that samples failed from fatigue when the maximum load exceeds 30% of the rated breaking strength (and the minimum load is zero). Samples do not fail by 200,000 cycles if the maximum load does not exceed 30%. Microphotographs of line filaments show the same characteristic fatigue failure mechanism as discovered by other investigators working on nylon filaments. It appears that a zero minimum load is a necessary condition for the fatigue failure of nylon filament. These results are made even more interesting by the fact that previous cyclic load tests (in which the minimum load never reached zero) shows no statistical reduction in tensile strength after 200,000 cycles of loading to loads as high as 62% of the rated breaking strength. This indicates that nylon line can be used at much higher loads if some tension is always kept in the line. Conversely, when nylon is used in a slack mooring situation, the maximum load must be reduced.

Field and laboratory abrasion tests were also conducted on nylon, polyester, and polypropylene line of the 8-strand plaited, double-braided, and 3-strand twisted constructions. Nylon and polyester line is generally three and two times more abrasion resistant, respectively, than polypropylene. Some samples were jacketed with polyurethane and the abrasion resistance was increased by approximately 5 to 6 times.

3.0 GENERAL DISCUSSION OF RESULTS

3.1 Three-Parameter Model of a Synthetic Mooring Line: A Brief Discussion.

The dynamic behavior of nylon and polyester mooring lines is best represented by the Maxwell three-parameter model. A brief explanation of this model will assist the reader in understanding the difference between dynamic and quasi-static elasticity, and hence, the significance of this work. A mechanical analog of the Maxwell three-parameter model is shown in figure 1. The spring constant K_0 represents the quasi-static behavior of the line and describes the elasticity of a mooring in a slow, long-term loading. It should be used to calculate the elongation of the mooring caused by current drag on the buoy. The quasi-state spring constant, K_0, is determined by a very slow unidirectional loading and is generally the type of information obtained from a manufacturer's brochure; it is often erroneously used to typify a mooring line in dynamic applications even though it is a quasi-static rather than a dynamic characteristic. The energy dissipation, or damping, mechanism of the line is represented by the dash pot having damping coefficient, N, and the spring having a spring constant K_1.

The two springs and dash pot have a combined effect called the apparent, or dynamic, spring constant, K_{ap}. The apparent spring constant describes the elasticity of a mooring in a dynamic condition such as wave loading. Figure 2 shows that the three-parameter model (Figure 2a) of a mooring line may be thought of, in the dynamic situation, as one spring of elasticity K_{ap} (figure 2b).

3.2 Apparent Spring Constant was Found to be Significantly Larger than the Quasi-Static Spring Constant

In general, the apparent spring constant, K_{ap}, is between three and four times greater than the quasi-static spring constant, K_0. Simply stated, this results in actual dynamic forces in a buoy mooring that are three to four times higher than those predicted when the quasi-static spring constant is mistakenly used to characterize the dynamic elasticity of the mooring during the design procedure. If the mooring line is thought of as a simple spring (figure 2 (b)), the tension amplitude (ΔT) is given by

$$\Delta T = K \Delta \varepsilon$$

where $\Delta\varepsilon$ is the strain amplitude in the mooring line during wave loading and K is the spring constant. This simple approximation shows that, for any given strain amplitude, ΔT is directly proportional to K. If K is actually larger than thought, (ie., using K_{ap} instead of K_0 for K) the tension amplitude will be greater. This could effectively reduce or negate the factor of safety in the mooring and anchor design. The difference between K_{ap} and K_0 can be illustrated by graphing both spring constants on the same axis (figure 3).

From the standpoint of elasticity in mooring design, it is preferable to use the smallest diameter line that is practical to obtain greater elasticity. (Note: That, of course, requires accurate prediction of mooring forces to allow the designer to work closer to the limit of the line. Inability to predict mooring forces is usually compensated for by increasing

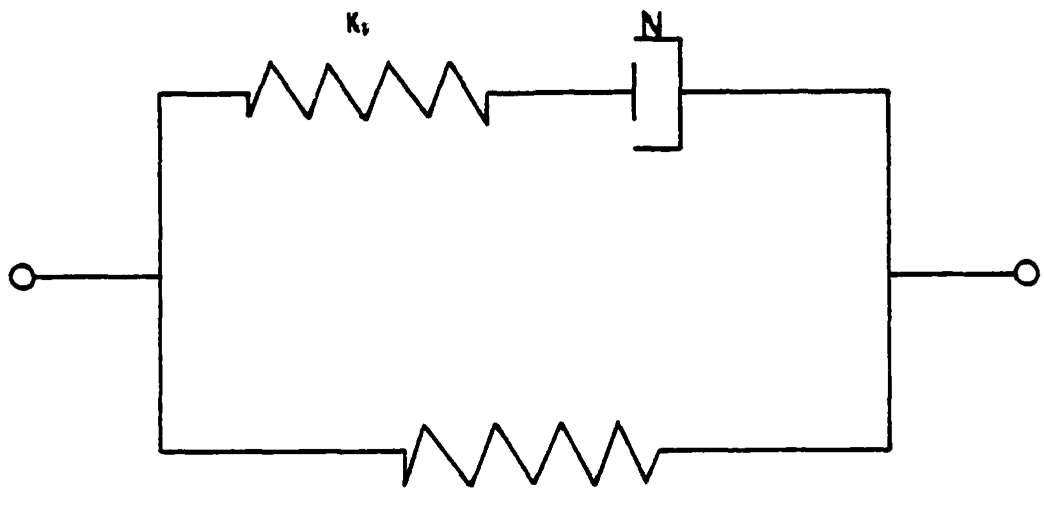


FIGURE 1

THREE-PARAMETER MODEL OF A VISCOELASTIC MATERIAL

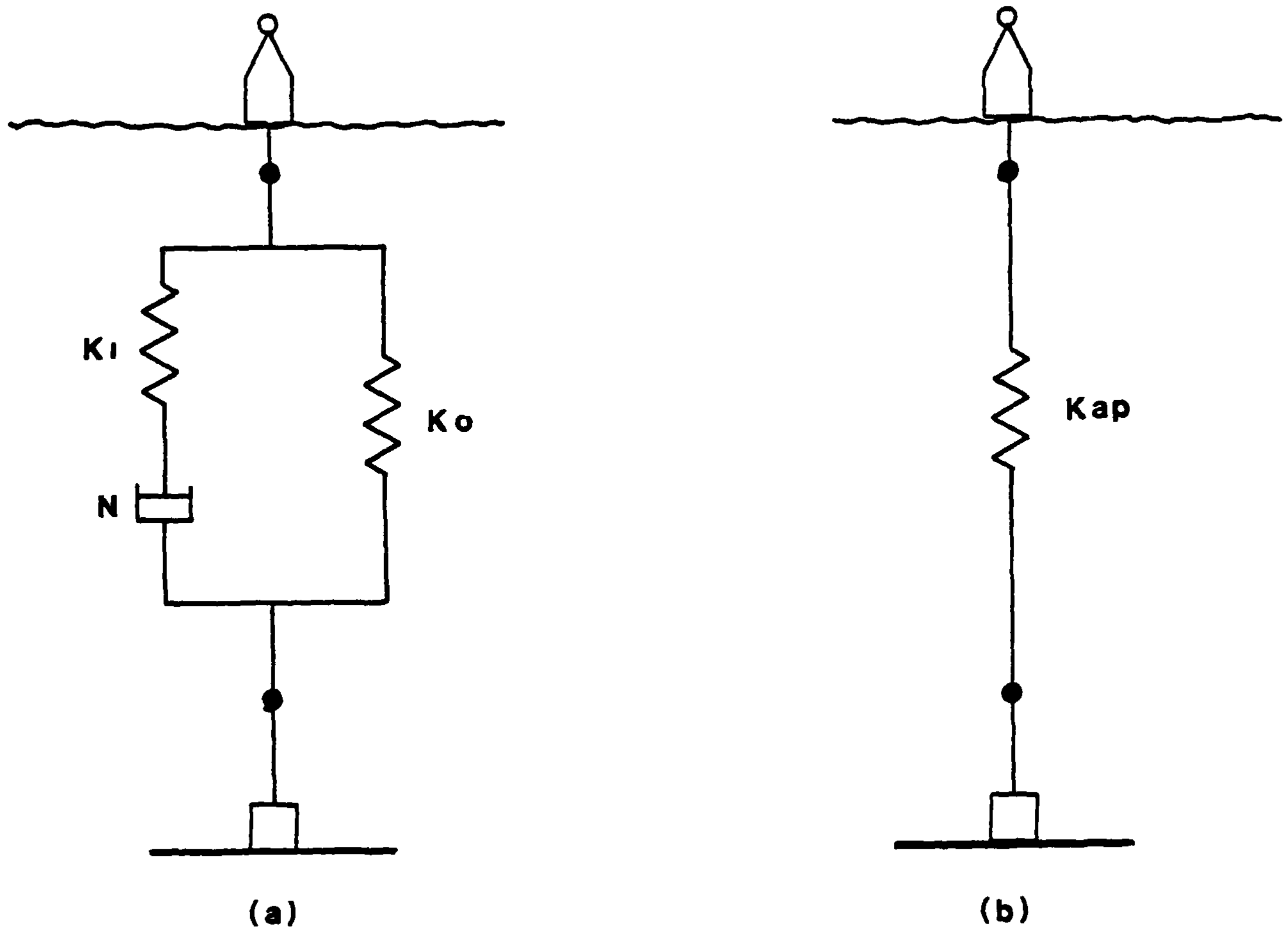


Figure 2

Equivalent Concepts of the Dynamic Elasticity of a Synthetic Mooring

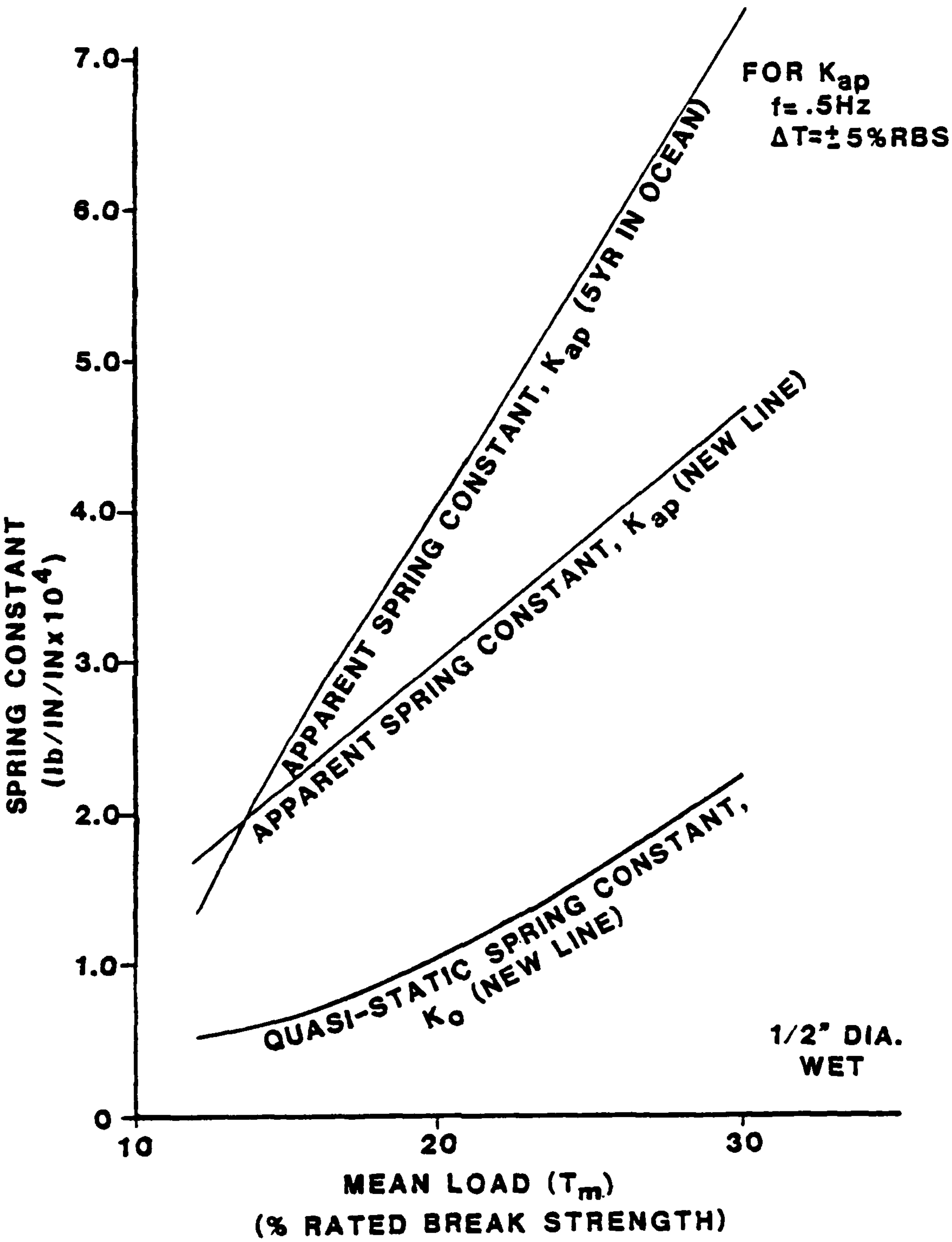


FIGURE 3

NYLON 8-STRAND PLAITED LINE SPRING CONSTANTS

the factor of safety, i.e., increasing line diameter, which may reduce the elasticity.) This point may be illustrated by observing the graphical representation of the relationship between the mean tension, tension amplitude and apparent spring constant for several line diameters. Assume that an application requires a maximum mean tension of 4,000 pounds and a maximum tension amplitude of approximately 1,600 pounds. Entering the mean tension axis of figure 4 at 4,000 pounds and following the line vertically, curves are intersected that represent the apparent spring constant of 3/4 inch, 1 inch and 1 1/4 inch diameter line in the range of 1,600 pounds load amplitude; they are 11-, 12-, and 17.5 X 10^4 lb/in/in, respectively. Clearly from the standpoint of elasticity, the smaller the diameter, the lower the spring constant and the more the mooring acts like a shock absorber and transmits less force to the anchor.

3.3 Nylon and Polyester Mooring Lines Generally Become Less Elastic After Immersion in the Ocean

The dynamic spring constant of nylon and polyester line generally increases after five years of exposure to the marine environment. The apparent spring constant of polyester 8-strand plaited and double braided line increased 30% and 17%, respectively; the apparent spring constant of nylon double braided and 8-strand plaited line increased approximately 100% and 18%, respectively. The apparent spring constant of nylon 8-strand plaited line field exposure samples are plotted in figure 3 and illustrates graphically that the apparent spring constant increases as a result of immersion in the ocean. At some time in the future, it may become practice to perform computer designs of new moorings using the apparent spring constant of "old" line to insure that the mooring will still meet the design conditions after, say, five years of service.

3.4 Nylon Line Can Fail at Relatively Low Loads Due to Snap Loading

Snap Loading is defined here as cyclic loading in which the minimum load in each cycle is zero and the maximum is some percentage of the rated breaking strength (RBS). Samples of 1/2 inch diameter 8-strand plaited line were cyclically loaded with a sine wave between zero and some percentage of the RBS until the line failed; the maximum dynamic load of the first test was approximately 70% RBS. The maximum load was reduced in subsequent tests until failure did not occur by 200,000 cycles. This point was reached at a maximum load of approximately 30% RBS. Other R&D Center cyclic test results suggest that the tensile strength of nylon line is not reduced if the minimum load does not reach zero and the maximum load does not exceed approximately 60% RBS. A preliminary design guideline might be stated: "if the line will always have some load in it, the maximum dynamic load may be as high as 60% RBS. If the minimum tension is expected to be zero, then the maximum dynamic tension should not exceed 30% RBS." This is discussed fully in section 5.0.

3.5 Nylon And Polyester Line Lose Strength Due To Exposure To The Marine Environment

The tensile strength of nylon and polyester double-braid and 8-strand plaited line is reduced by approximately 50% after 5 years of exposure to the marine environment. Limited data indicates that, for polyester line, the strength loss is approximately linear with the time of its exposure to the marine environment. This is discussed fully in section 4.4.4.

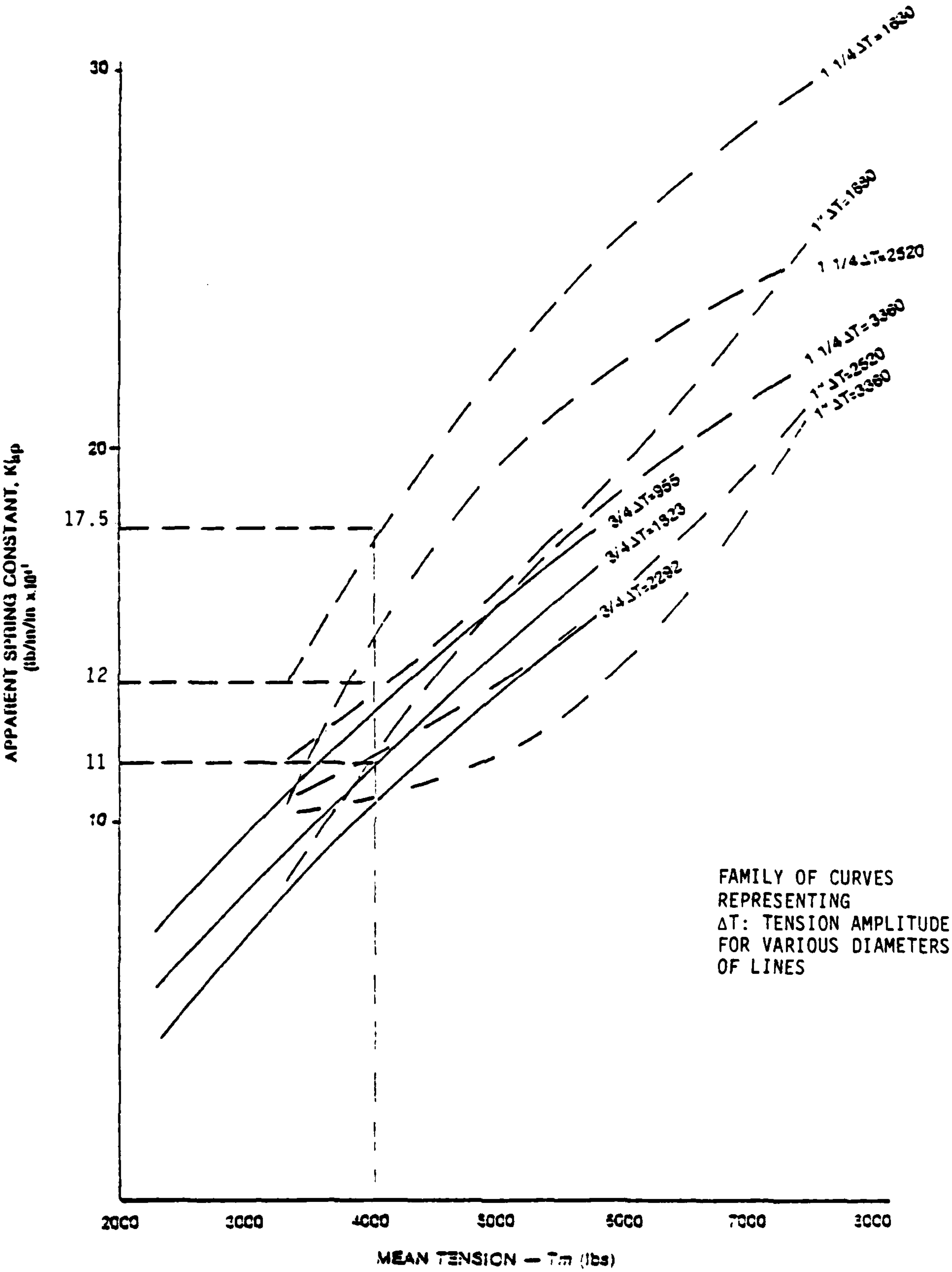


FIGURE 4

APPARENT SPRING CONSTANT, K_{ap}, CURVES FOR NYLON DOUBLE BRAID LINE, NEW, WET.

4.0 THE DYNAMIC PROPERTIES OF NYLON AND POLYESTER LINE

4.1 Background

A quantitative description of the static and dynamic properties of synthetic lines is a necessary input to a shallow-water mooring dynamics computer program. Without accurate material coefficients, it will be difficult to determine if a model is giving incorrect answers because it cannot model the physics of the mooring or because the input material coefficients are not correct. In addition to determining the required material coefficients, it is necessary to understand how the anticipated loading factors interact with the various material properties so that effective trade-offs can be made during the design process (i.e., "tuning" the design).

To quantify the dynamic properties of selected synthetic mooring materials, an investigation was undertaken along two parallel paths: (a) laboratory tests in which the factors affecting synthetic line properties were investigated in detail in a machine built especially for the purpose; and (b) field exposure tests in which synthetic line was subjected to the marine environment. The laboratory tests provide detailed understanding of the characteristics while the field exposure tests provide a link between the "real world" and the controlled conditions of the laboratory.

A Screening Experiment was conducted to determine the effect of frequency, mean load, load amplitude, duration and diameter, on the static and dynamic properties of nylon line. The results of that experiment were used to eliminate some variable so that a more detailed experiment could be performed using fewer variables and a lower number of samples. While the results of the Screening Experiment were informative and useful in planning the tests that follow, the results are not discussed here but are discussed in detail in appendix A. Where required, specific results from the Screening Experiment are brought forward for comparison with the results of the full-scale tests discussed in this section.

4.2 Three-Parameter Model Of A Viscoelastic Material

The Maxwell three-parameter model of a viscoelastic material is investigated with respect to synthetic mooring materials because (a) it is thought to predict the dynamic behavior of the mooring line better than a single-spring element model; (b) the structure of the three-parameter model provides an insight to the behavior of the line; (c) even if the three-parameter model is found not to be necessary in its entirety, the data collected to investigate it can be used in other models or an independent model constructed; and (d) it is the mooring line model that is used in the NOAA Data Buoy Model (a computer model under consideration as a mooring design tool) and accurate coefficients for this line model are necessary to operate and evaluate that mooring model.

A mechanical analog of the Maxwell three-parameter model is shown in figure 1. The spring constant, K_0, represents the quasi-static behavior of the line. It is determined by a very slow pull-to-failure and is generally the type of information obtained from a manufacturer's brochure;

it is often incorrectly thought to typify the line even though it is a quasi-static, rather than a dynamic, characteristic. The energy dissipation mechanism is represented by the dashpot, having a damping coefficient, N, and the spring, having a spring constant of K_1.

The expression (Reid, 1968)

$$\tau = \frac{N}{K_1}$$

is the characteristic relaxation time of the line.

The springs and dashpot have a combined effect called the apparent spring constant (K_{ap}) which is the slope of a hysteresis loop for one cycle of loading (figure 5). It is given by (Reid, 1968):

$$K_{ap} = \left[\frac{K_o^2 + (K_o+K_1)^2(\omega\tau)^2}{1 + (\omega\tau)^2}\right]^{1/2} \tag{1}$$

Equation (1) gives the apparent spring constant of the line as a function of frequency ω. If $\omega\tau$ is much greater than one,

$$K_{ap} = K_1 + K_o \tag{2}$$

If $\omega\tau$ is much less than one,

$$K_{ap} = K_o \tag{3}$$

In summary, equation 1 predicts that the dynamic stiffness of the line is frequency dependent, never less than the quasi-static value, and increases with frequency. The difference between the maximum (equation 2) and minimum (equation 3) values of K_{ap} is, therefore, a function of the internal damping of the line.

Hysteresis (H) is the amount of energy dissipated by the line during one cycle. It is defined by the equation (Reid, 1968):

$$H = \oint T_m \, \partial\epsilon \tag{4}$$

or

$$H = \frac{K_1(\Delta T)^2 \omega\tau}{K_o+(K_o+K_1)^2(\omega\tau)^2}$$

where ΔT, T_m, ω, and ε are load amplitude, mean load, frequency and strain, respectively. Graphically, it is the area inside the hysteresis loop shown in figure (5a).

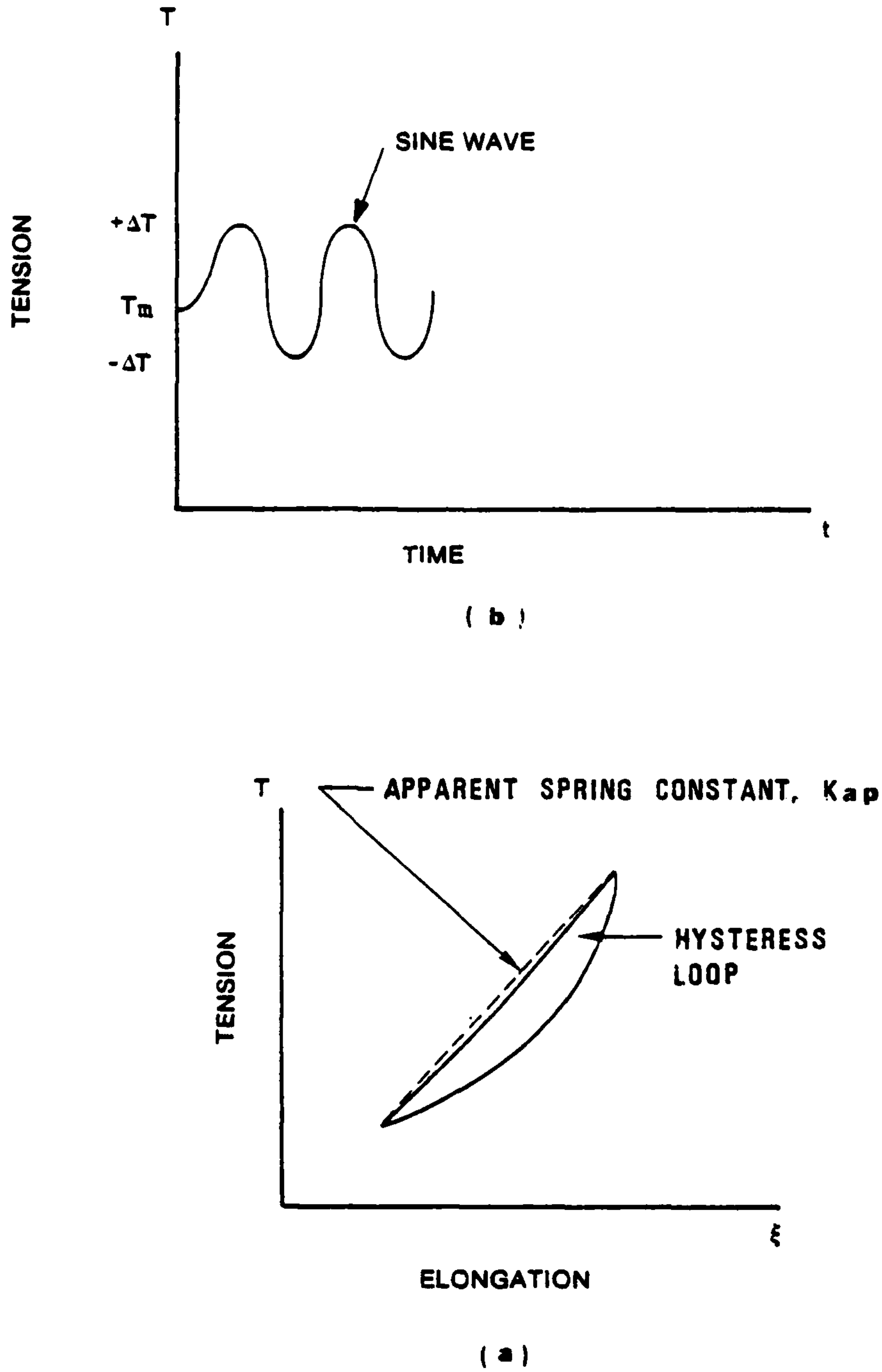


FIGURE 5
CYCLIC LOADING SCHEMATIC AND HYSTERESIS LOOP

4.3. Test Procedure And Experimental Design

Tests were undertaken to model the dynamic properties of new and used synthetic mooring lines incorporating the frequency of excitation (f), mean load (T_m), and load amplitude (ΔT) factors. The loading scheme is shown in figure 5(b). The factor levels, shown in table 1, were selected so that the experimental range brackets the conditions in which the line is likely to be used. This bold experimental approach makes it easier to detect the reaction of the line property to variations in the factors. Three levels of each factor are used so that the variation of line response in the entire experimental region can be determined. The factor levels (in pounds rather than percent of break strength) for one-inch diameter line were used in the test of 1-1/4-inch diameter line because the rated breaking strength of 1-1/4-inch line, when applied to the factor levels in table 1, would require tensions in excess of the capability of the cyclic/tensile test machine.

Four diameters of new nylon line were tested individually so that the results would be as accurate as possible. It is possible to include diameter as a fourth variable; however, that would probably reduce the accuracy of the results obtained. Since the screening experiment (appendix A) showed that the number of cycles (up to 200,000 cycles tested in that experiment) does not significantly affect the dynamic properties of the line, each sample was cycled to a low number of cycles (i.e., 100 cycles) at each new load level just to "break in" the line at that load range before recording the apparent spring constant and hysteresis loop. Four samples of each line diameter were terminated with eye-splices and stored in fresh water for several days before the test. It is felt that fresh water, rather than salt water, is adequate in such a short test because the lubricating and cooling effect of the water is probably much more important than the effect of salt content on the chemical properties of the line. Half-inch diameter and 3/4-inch diameter samples were approximately five feet long and the 1-inch and 1-1/4-inch diameter samples were approximately six feet long.

For the field exposure tests, samples of 1/2-inch diameter nylon and polyester line of 8-strand plaited and double-braided construction were deployed as part of the mooring of lightweight plastic buoys. Since it was not the objective of this particular experiment to determine the abrasion resistance characteristics of a synthetic mooring line, the synthetic line section was shorter than the water depth and the remainder of the mooring was 1/2-inch galvanized chain. The synthetic lines were terminated with eye-splices/NEWCO thimbles applied by the line manufacturer. Tensions up to 150 pounds were measured in the moorings during the early period of deployment. Since this is a small percentage of the rated breaking strength, it may be concluded that any change in line properties is probably due to exposure to the general marine environment rather than loading to any substantial level.

Each sample was submerged in fresh water during the dynamic test. The factor levels in tables 1 and 2 are converted to "pounds tension" based on the rated breaking strength of each line and assembled into 15 combinations of mean load, load amplitude, and frequency according to the Box-Behnken experimental design technique. The combinations, or runs, are

TABLE 1

Dynamic Test Factor Levels For Nylon Double Braid New Line

	FACTOR LEVELS					
	FOR 1/2" and 3/4" Dia.			FOR 1" and 1 1/4" Dia.		
FACTORS	-1	0	+1	-1	0	+1
Frequency (X_1) Hz	.1	.3	.5	.1	.3	.5
Mean load (X_2) %RBS	12	21	30	10	16	22
Load amplitude (X_2) %RBS	± 5	± 8.5	± 12	± 5	± 7.5	± 10

RBS-Rated Break Strength

	Diameter (inches)			
	1/2	3/4	1	1 1/4
Rated Break Strength-RBS	6400(1)	19,100(2)	33,600(2)	(3)

(1) Experimentally measured, Bitting 1975.
(2) Taken from Samson catalog.
(3) The Rated Break Strength (RBS) of 1" diameter line is used on the 1 1/4" diameter line test because the RBS of 1 1/4 applied to the factor table above would require testing at a tension greater than the capacity of cyclic/tensile test machine.

TABLE 2

Dynamic Test Factor Levels
Four And Five Years Field Exposure Samples

FACTOR	FACTOR LEVEL		
	-1	0	+1
Frequency (f Hz)	.1	.3	.5
Mean Load T_M (%RBS)	12	21	30
Load Amplitude ΔT (%RBS)	± 5	± 8.5	± 12

RBS - Rated Break Strength

MATERIAL/CONSTRUCTION/DIA.	RBS	SOURCE OF INFORMATION
Nylon Double Braid (1/2")	6400	(1)
Nylon 8-Strand Plait (1/2")	5760	(2)
Polyester Double Braid (1/2")	7000	(1)
Polyester 8-Strand Plait (1/2)	6600	(1)

(1) From Bitting, 1975.

(2) Manufacturer's rated break strength with 10% strength reduction applied for wet tests.

ordered so that the peak loading increases from one run to the next. That way the line is always tested at successively higher loads. Use of the Box-Behnken experimental design allows an economy in experimentation effort through the technique of hidden replication. Three factors are tested at three levels in only 15 observations rather than the 27 observations normally used in a full factoral design.

During each run, the apparent spring constant and hysteresis are recorded and the dissipation spring constant and characteristic relaxation time are calculated from simulataneous solution of equations (1) and (4). That solution technique requires the use of K_0, the quasi-static spring constant which is measured in a slow uni-directional load (approximately 10 inches/minute) performed 24 hours after the dynamic test.

Each set of line parameters (the 15 values of K_{ap}, K_1, H, and τ) is processed by the Box-Behnken experimental design technique which regresses experimental results into an empirical equation that relates the input factors (i.e., frequency, mean load, and load amplitude) to the response (i.e., K_{ap}, H, etc.). The regression equation is:

$$Y = B_1 + B_2X_1^2 + B_3X_2^2 + B_4X_3^2 + B_5X_1 + B_6X_2 + B_7X_3 + B_8X_1X_2 + B_9X_1X_3 + B_{10}X_2X_3 \quad (5)$$

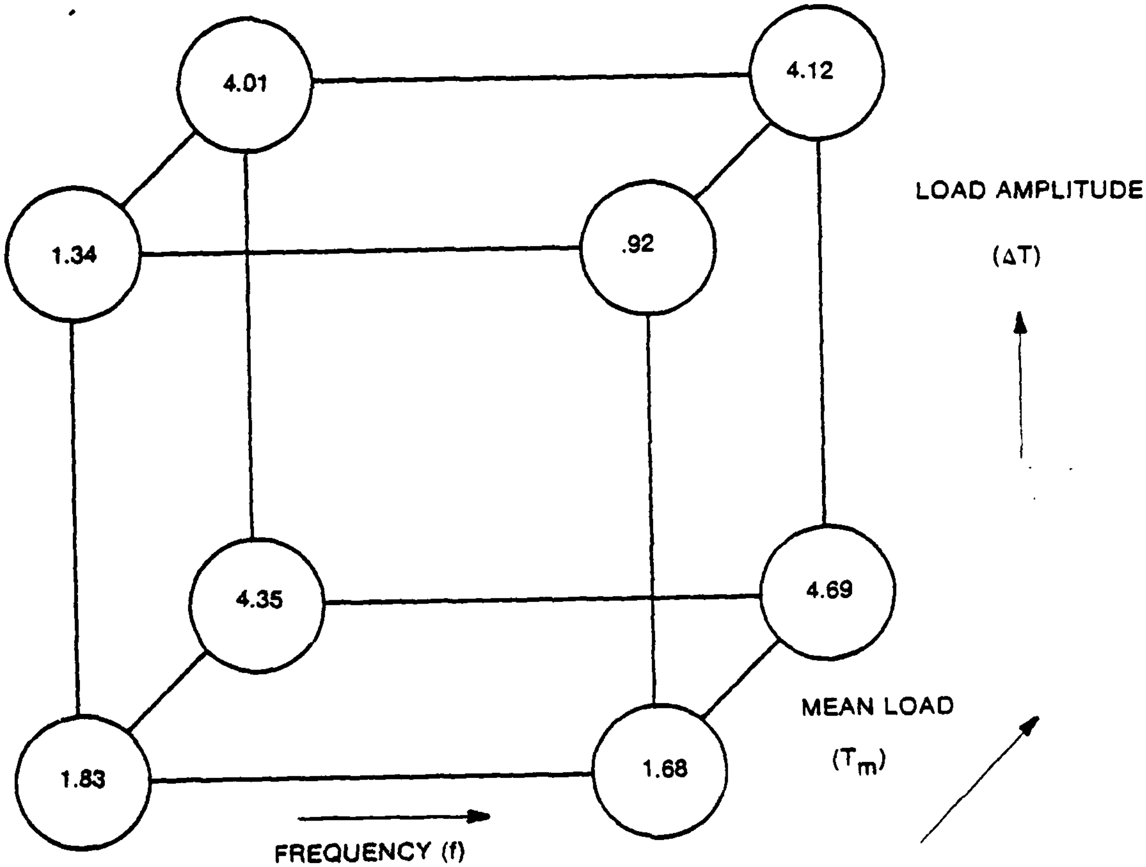
This equation includes the mean value (B_1), the first and second order (B_2-B_7) of frequency (X_1), mean load (X_2), and load amplitude (X_3). Coefficients B_8 to B_{10}, indicating the combined effect of two factors on the line property, are called interactions. Equation (5), the "coded equation," cannot be used easily to calculate the response, Y. Refer to appendix C for conversion to engineering units. An alternate form of eqn 5 is:

$$Y = B_1 + B_2f^2 + B_3T_m^2 + B_4\Delta T^2 + B_5f + B_6T_m + B_7\Delta T + B_8f\,T_m + B_9f\Delta T + B_{10}T_m\Delta T \quad (5a)$$

The relative magnitude of the coefficients of Equation (5) (i.e., B_2, B_3, ...) indicates which factor has the greatest effect on the line properties that the equation models. It must be emphasized that the equation models line only in the experimental regime from which the data was taken. The applicable range of use of each equation is shown at the bottom of the table containing regression equation coefficients for a particular line property. In addition to inspecting the magnitude of the coefficient, data may be graphically interpreted by placing the values of the line properties as predicted by the equation on the cube as shown in figure 6. Each corner on the cube represents the extreme of the experimental regime tested. By inspecting the trend of high and low values for the three variables (the factor increases in the direction of the arrow), it may be possible to identify the variable that has the least effect on the line property. Holding that variable constant, the other two can be plotted on a three-dimensional response surface. This technique will be illustrated as it is used in later sections.

In the tables of polynomial equation coefficients shown in the remaining text, "F-Stat" is the F statistic calculated from the data. "F-Crit" is the F statistic taken from statistical tables. If F-Stat is greater than F-Crit, the experimental data fits equation 5 with a 95% confidence limit.

FREQUENCY (f): 0.1 Hz - 0.5 Hz
MEAN LOAD (T_m): 12% RBS - 30% RBS
LOAD AMPLITUDE (ΔT): ±5% RBS - ±12% RBS
1/2" DIAMETER, NEW, WET



APPARENT SPRING CONSTANT, K_{ap} (lb/in/in)
($\times 10^4$)

FIGURE 6

EXPERIMENTAL CUBE — APPARENT SPRING CONSTANT (K_{ap}) FOR NYLON 8-STRAND PLAITED LINE (NEW)

4.4. Results

4.4.1 Apparent Spring Constant, K_{ap}

The regression equation coefficients for the apparent spring constant, K_{ap}, of new nylon and polyester line are shown in table 3. Inspection of these coefficients indicates the effect of each factor on the apparent spring constant. First-order effect of mean load (T_m) and load amplitude (ΔT) generally exhibit the largest coefficients (i.e., B_6 and B_7, respectively). Second-order effect of mean load (B_3) and load amplitude (B_4) are small compared to the first-order effect and the mean value (B_1). The apparent spring constant can be characterized as primarily (a) a function of mean load and load amplitude, and (b) a mostly linear relationship. It is interesting to note that K_{ap} is almost independent of frequency in the range of 0.1 to 0.5 Hz. To illustrate, if the mean load and load amplitude are held constant, frequency changes K_{ap} by only 6% in 1/2-inch diameter nylon double-braided line and 11% in 1-inch diameter double-braided line. By contrast, varying mean load over the entire experimental range and holding frequency constant, K_{ap} is changed by approximately 200%.

The regression equation coefficients for K_{ap} of nylon and polyester field-exposure samples are shown in table 4 and table 5, respectively. The apparent spring constant of nylon double-braided line increases approximately 99% over 5 years (table 4). Premature tensile failure during the dynamic testing and losses in the field reduced the sample size of nylon 8-strand plaited line to two samples each from 4 and 5 years of exposure. For that reason and because of the high variability of the data, that data is reported for documentation purposes but no inference is drawn from it.

The apparent spring constant of polyester 8-strand plaited line increases approximately 30% during 4 years of exposure. Because of the small number of data points from polyester double-braided line for 5 years of exposure, it is combined with the 4-year data. Considering that, the apparent spring constant increases 17% as a result of exposure (table 5).

One of the most striking aspects of the data from the field-exposure samples is the larger relative variability (i.e., the standard deviation divided by the mean value). For new line, relative variability is typically approximately 10% whereas for the field-exposure samples, it is typically approximately 50%. This is why only general inferences can be made about some field data and combined data points are helpful where possible.

Holding the least significant factor constant (in this case, frequency) and solving equation (5) with the coefficients from table 3, a three-dimensional curve of K_{ap} can be developed. Figure 7 is such a plot for 1/2-inch diameter nylon plaited line. All points taken together form a response surface which represents the apparent spring constant for all combinations of T_m and ΔT.

The shaded surface in figure 7 represents the apparent spring constant of new line. For new line, K_{ap} increases as ΔT decreases and increases dramatically as mean load increases. That is to say, high values of K_{ap} occur at high values of T_m and low values of ΔT.

TABLE 3

Apparent Spring Constant, K_{ap}, Polynomial Equation Coefficients For New, Wet Line

(lb/in/in x 10^4)

FACTOR	COEFFICIENT	POLYESTER (1/2") (DIAMETER) 8-Strand Plait	POLYESTER (1/2") (DIAMETER) Double Braid	NYLON 8-Strand Plait (1/2")	NYLON DOUBLE BRAID (Diameter) 1/2"	NYLON DOUBLE BRAID (Diameter) 3/4"	NYLON DOUBLE BRAID (Diameter) 1"	NYLON DOUBLE BRAID (Diameter) 1 1/4"
MEAN	B_1	6.317	9.457	3.088	3.451	11.867	14.577	19.790
f^2	B_2	.069	-.578	-.111	0.0	.102	-.697	-1.067
T_m^2	B_3	-.276	-.198	.001	-.031	-.703	-.330	-1.977
ΔT^2	B_4	-.188	-.284	-.104	.029	.038	.298	.680
f	B_5	.201	.271	-.019	.105	.098	-.456	-.068
T_m	B_6	2.059	1.973	1.422	1.677	5.562	6.872	7.341
ΔT	B_7	-.058	-.319	-.274	-.274	-1.278	-2.369	-3.208
f, T_m	B_8	.260	-.067	.131	.065	.109	.100	1.380
$f, \Delta T$	B_9	.047	.100	-.060	.100	.325	-.432	-.138
$T_m, \Delta T$	B_{10}	-.003	.464	.047	-.095	.065	-1.705	-.607
	r^2	.985	.977	.998	.999	.995	.993	.983
	F-STAT	26.98	17.248	161.33	582.04	80.2	55.41	23.248
	F-CRIT	3.48	3.48	3.48	3.48	3.48	3.48	3.48
RANGE OF USEFULNESS OF EQUATION	f (Hz)	.1 - .5						
	T_m (lbs)	792 - 1980	768 - 1920	691 - 1728	768 - 1920	2292 - 5730	3360 - 7392	3360 - 7392
	ΔT (lbs)	$\pm$330-$\pm$792	$\pm$320-$\pm$768	$\pm$288-$\pm$691	$\pm$320 - $\pm$768	$\pm$955 - $\pm$2292	$\pm$1680 - $\pm$3360	$\pm$1680 - $\pm$3360

Table 4

Nylon Line Field Exposure Polynomial Equation Coefficients For Apparent Spring Constant, K_{ap}(½" Dia Line)

($lb/in/in \times 10^4$)

FACTOR	POLYNOMIAL EQUATION COEFFICIENT	NYLON PLAITED NEW	NYLON PLAITED FIELD EXPOSURE 4 YEAR (1)	NYLON PLAITED FIELD EXPOSURE 5 YEAR (1)	NYLON DOUBLE-BRAIDED NEW	NYLON DOUBLE-BRAID 5 YEAR
MEAN	B_1	3.088	9.100	3.668	3.451	6.88
f^2	B_2	-0.111	-0.138	.154	0.0	.501
T_m^2	B_3	0.001	-1.238	-.073	-0.031	.944
ΔT^2	B_4	-0.104	0.288	.047	0.029	-.404
f	B_5	-0.019	0.412	.238	0.105	-.916
T_m	B_6	1.422	3.213	2.124	1.677	4.647
ΔT	B_7	-0.274	-0.825	-.668	-.274	.979
f, T_m	B_8	0.131	-0.125	.199	.065	-1.61
$f, \Delta T$	B_9	-.060	0.150	.363	.100	.963
$T_m, \Delta T$	B_{10}	0.047	-1.050	-.669	-.095	-.710
	r^2	0.998	0.955	.969	.999	.978
	F-STAT	161.339	8.456	12.546	582.04	17.668
	F-CRIT	3.480	3.480	3.480	3.48	3.48
	Number of Lines Tested	3	2	2	3	4
	Change in K_{ap}		(1)	(1)	100%	
USEFUL RANGE OF EQUATION:	f (Hz)	.1 - .5				
	T_m(lbs)	691 - 1728			768 - 1920	
	ΔT(lbs)	±288 - ±691			±320 - ±788	

(1) Limited data available because of premature failure during dynamic test or loss during field deployment. No analysis performed on this data.

TABLE 5

Polyester Line Field Exposure Polynomial Equation Coefficients For Apparent Spring Constant, K_{ap}(1/2" Dia Line)

(lb/in/in x 10^4)

FACTOR	POLYNOMIAL EQUATION COEFFICIENT	POLYESTER PLAITED NEW	POLYESTER PLAITED FIELD EXPOSURE 4 YEAR	POLYESTER PLAITED EXPOSURE 5 YEAR (1)	POLYESTER DOUBLE-BRAID NEW	POLYESTER DOUBLE-BRAID 4 YEAR	POLYESTER DOUBLE-BRAID 5 YEAR
MEAN	B_1	6.317	8.252		9.457	11.55	10.317
f^2	B_2	0.069	0.381		-.578	-2.399	-.133
T_m^2	B_3	-0.276	1.334		-.196	1.406	-.259
ΔT^2	B_4	-0.118	-1.123		-.284	-0.631	-.028
f	B_5	0.201	0.334		.271	0.121	.129
T_m	B_6	2.059	0.733		1.973	4.689	4.18
ΔT	B_7	-0.058	-0.029		-.319	-0.300	-1.987
f, T_m	B_8	0.260	0.401		-.067	0.148	.380
$f, \Delta T$	B_9	0.047	0.275		.100	-0.230	.429
$T_m, \Delta T$	B_{10}	-0.003	-0.672		.464	1.640	.705
	r^2	0.985	0.748		.977	0.994	.986
	F-STAT	26.988	1.185		17.298	62.155	28.49
	F-CRIT	3.480	3.480		3.48	3.480	3.48
	No. of Lines Tested	4	5	0	3	4	2
	Change in Kap		30%			17%	
USEFUL RANGE OF EQUATION:	f (Hz)	.1 - .5					
	T_m (lbs)	792 - 1980			840 - 2100		
	ΔT (lbs)	±330 - ±792			±350 - ±840		

(1) Data not available

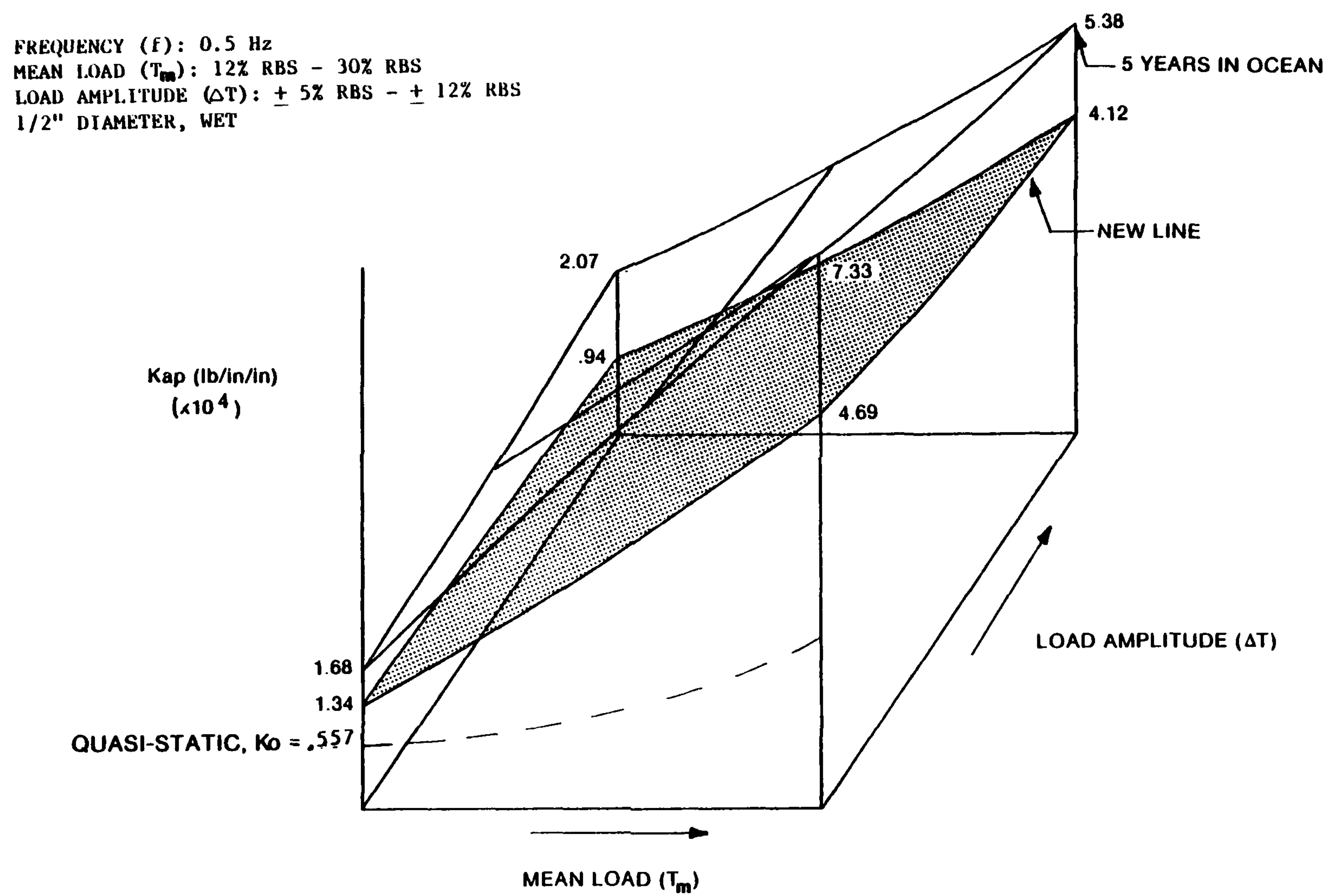


Figure 7

**APPARENT SPRING CONSTANT (Kap) RESPONSE SURFACE-
NYLON 8-STRAND PLAITED LINE**

The transparent surface in figure 7 represents the apparent spring constant of the exposure samples. It is observed from figure 7 that the K_{ap} does increase with exposure to the marine environment.

Also shown on figure 7 is the quasi-static spring constant, K_o. It represents the slope of the load-strain curve recorded during a slow uni-directional loading like a tensile test. That data is readily available in line manfacturers' catalogs. Unfortunately, it is a quasi-static characteristic that some mooring designers apply in dynamic applications. The quasi-static spring constant is approximately 3 to 4 times smaller than the apparent spring constants in general. This means that, if K_o is used in a dynamic application rather than K_{ap}, the actual loads may be between 3 and 4 times greater than predicted (for a given displacement); that basically nullifies the factor of safety normally assigned during the design process. It also means that in a buoy mooring, for example, the line will act less like a shock absorber and transmit more force to the anchor. The quantification of this phonomenon is one of the most significant results of this investigation.

Comparing B_1 coefficients in table 3 offers a general comparison of the apparent spring constant of various lines. The B_1 coefficient for nylon plaited and polyester plaited line (i.e., 3.088 and 6.317, respectively) shows that polyester is twice as stiff as nylon. Double-braided line is also stiffer than plaited. From the standpoint of elasticity in mooring design, it is preferable to use the smallest diameter line that is practical to take advantage of greater elasticity as discussed in section 3.2.

4.4.2. Quasi-Static Spring Constant, K_o

The quasi-static spring constant K_o is the elasticity of a line under a slow uni-directional loading. It is the slope of the load-strain curve. Because K_o is nonlinear for some materials, it must be calculated at the mean load level of interest and used for small perturbations around that mean load. Because of the nonlinearity of nylon (figure 8 and table 6) it cannot be used to calculate the static length of a mooring except at very low loads. For that calculation, the load-strain equations in section 4.4.3 must be used. The quasi-static spring constant of 1/2-inch diameter polyester 8-strand plaited line generally increases somewhat with field exposure. Polyester double-braided line undergoes a significant reduction in K_o at low loads and increases with load. See figure 9 and table 7. This indicates a significant departure from the nearly linear load-strain curve and constant K_o of new line (see figure 9 and table 6). This observation is confirmed by the load-strain curves discussed in section 4.4.3. This marked deviation has not been explained. The quasi-static spring of nylon 8-strand plaited and double-braid line increases with exposures to the marine environment (see figure 10 and table 7). No distinction is made between four and five-year field exposure samples. In general, the data does not support that distinction and all data were combined and will be identified simply as field exposure samples.

The curves in figure 8 show the variation in K_o with tension. Again, as discussed in section 3.2, the importance of using the line with the lowest elasticity is evident. If the required mean load (T_m) is assumed to be 1000 pounds, figure 8 indicates that 1/2-inch

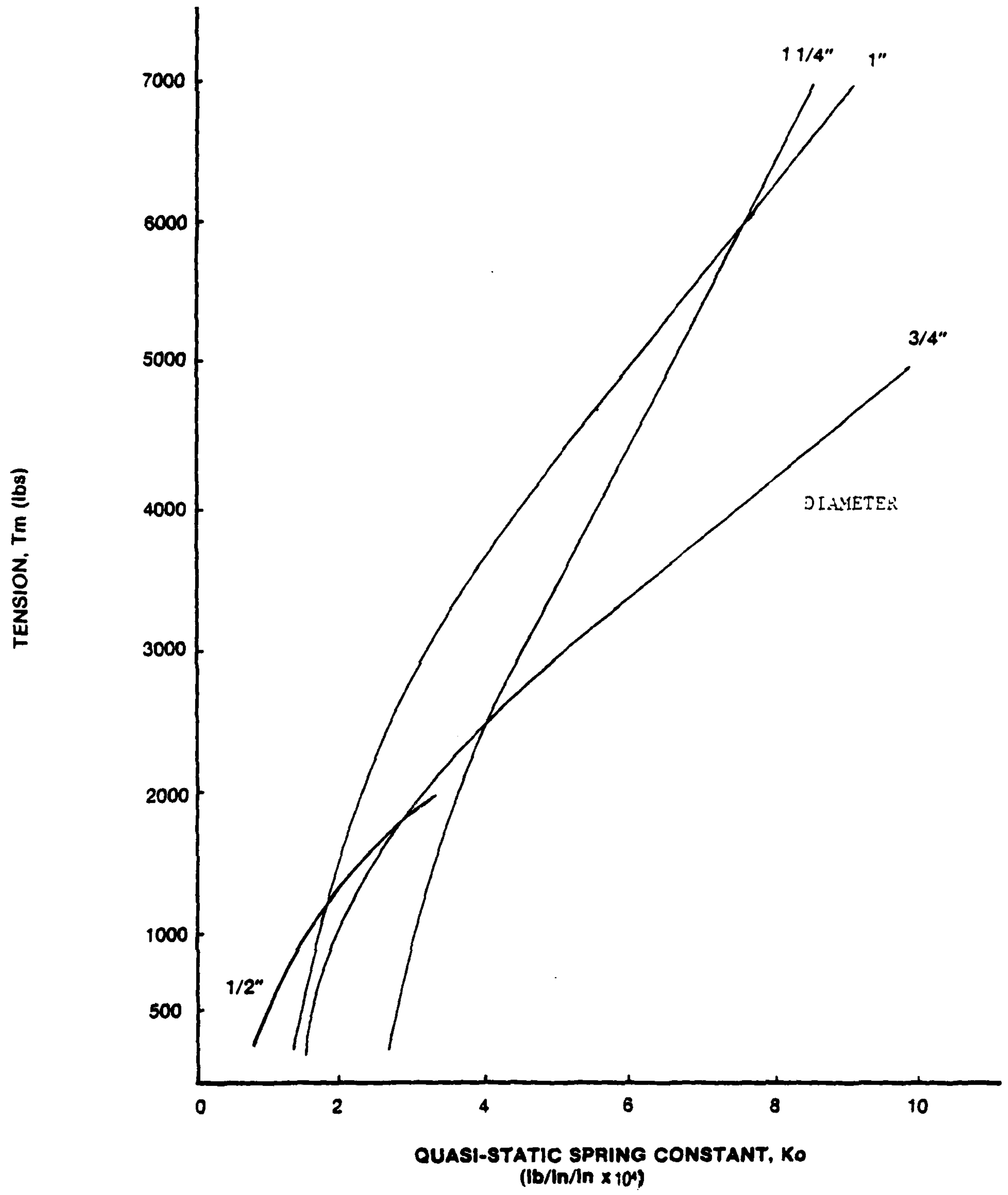


FIGURE 8

QUASI—STATIC SPRING CONSTANT, Ko, OF NYLON DOUBLE BRAID LINE, NEW, WET.

TABLE 6

Quasi-Static Spring Constant, Ko, Equations For Nylon And Polyester Line (New, Wet)

$$K_o \left(\frac{\text{lbs}}{\frac{\text{in}}{\text{in}}}\right) = \left(A + BT_m + CT_m^{\ 2} + DT_m^{\ 3}\right) \times 10^4$$

	Diameter	A	B x 10^{-4}	C x 10^{-7}	D x 10^{-11}	Range of Usefulness (lbs)	Number of Samples
Nylon, Double Braid	1/2"	.698	5.80	-2.24	3.26	1720	4
	3/4"	1.477	-.329	5.035	-3.25	5730	4
	1"	1.492	-1.52	3.008	-1.798	8400	4
	1 1/4"	2.66	2.46	1.670	-1.208	7800	4
Nylon, 8-Strand Plaited	1/2"	-1.02	44.8	-42.3	158	2363	9
Polyester, Double Braid	1/2"	2.327	73.12	-41.35	53.04	1920	3

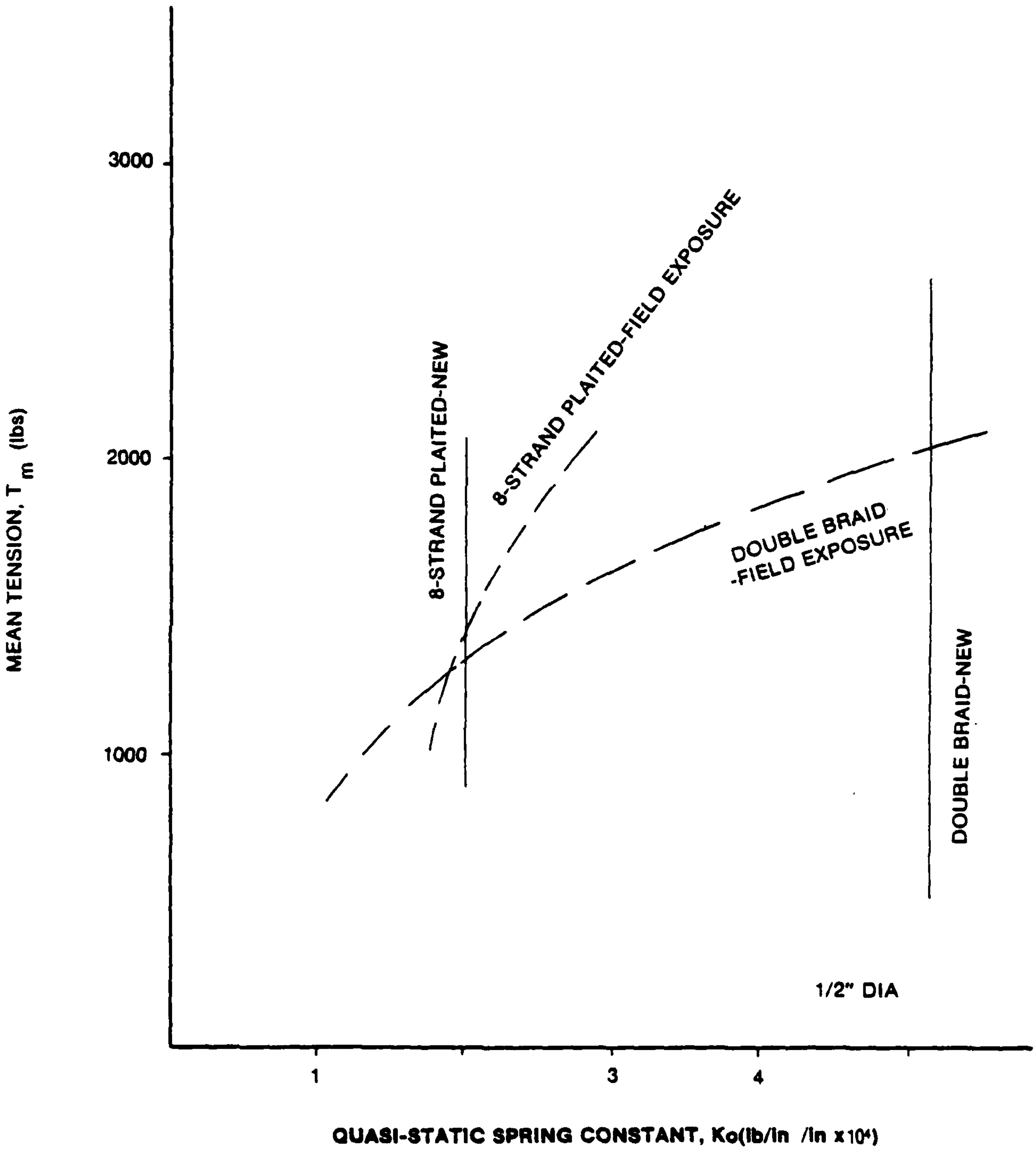


FIGURE 9

QUASI-STATIC SPRING CONSTANT, Ko, OF POLYESTER LINE AFTER EXPOSURE TO THE MARINE ENVIRONMENT

TABLE 7

Quasi-Static Spring Constant, Ko, Equations For Field Exposure Samples

$$K_o\left(\frac{\frac{lbs}{In}}{In}\right) = \left(A + BT_m + CT_m^{\ 2} + DT_m^{\ 3}\right) \times 10^4$$

MATERIAL/CONSTR.	A	B x 10^{-4}	C x 10^{-7}	D x 10^{-11}	RANGE OF USEFULNESS (lbs)
Nylon Double Braid - New	.698	5.80	-2.24	32.6	2400
Nylon Double Braid - Field Exposure	1.93	-37.1	29.76	0.0	2700
Nylon 8-Strand Plaited - New	-.49	36.22	28.1	81.03	2000
Nylon 8-Strand Plaited - Field Exposure	-1.02	44.8	-42.3	158.	2000
Polyester Double Braid - New	2.327	73.12	-41.35	53.04	2500
Polyester Double Braid - Field Exposure	.701	4.68	-49.8	67.2	2000

1/2" Diameter Lines

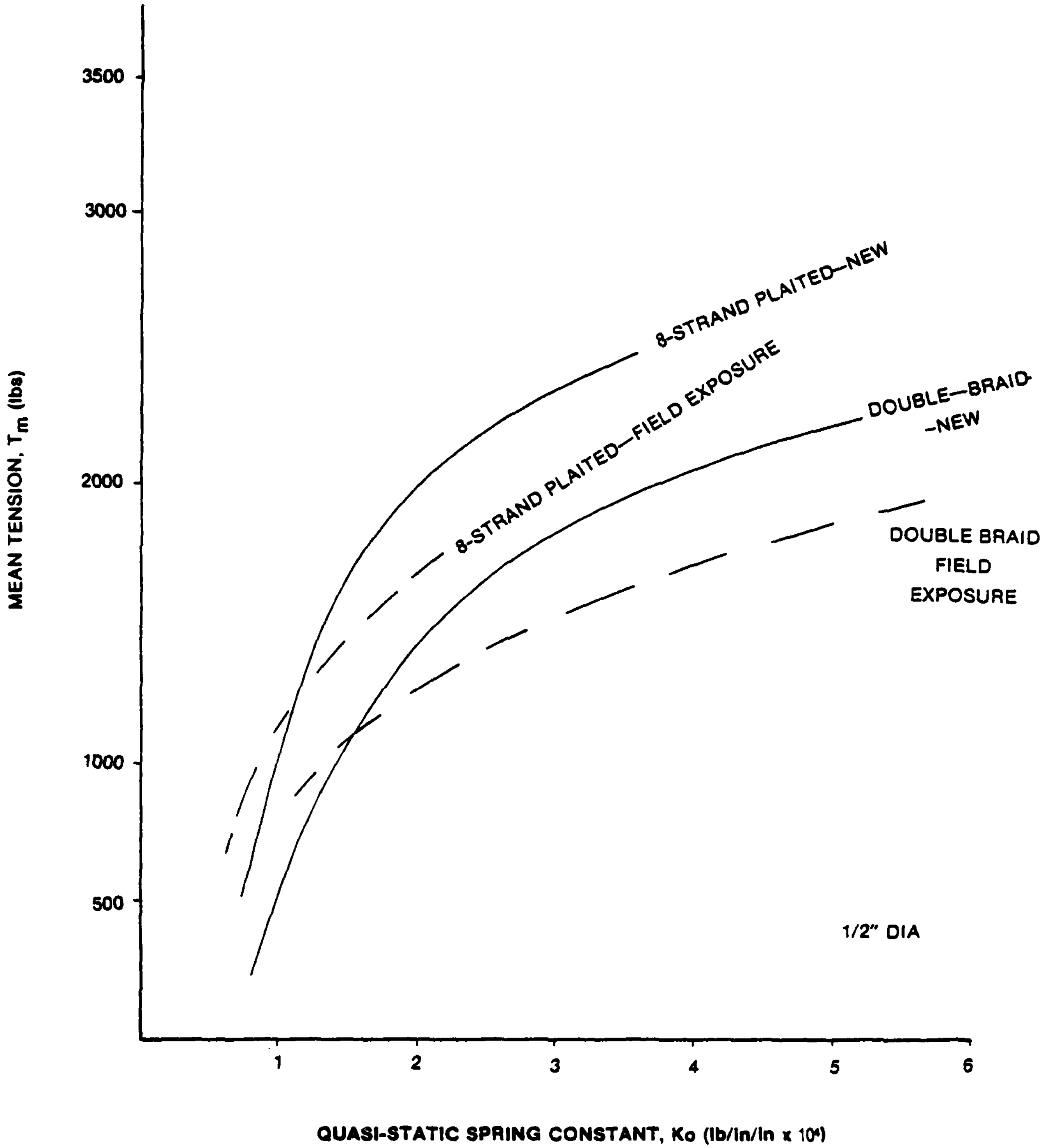


FIGURE 10

QUASI-STATIC SPRING CONSTANT, Ko, OF NYLON LINE AFTER EXPOSURE TO THE MARINE ENVIRONMENT.

diameter line has the lowest spring constant. If the required mean load is increased to 2000 pounds, the 1-inch diameter line would provide the lowest quasi-static spring constant. This is explained by the fact that the increase from 1000 pounds to 2000 pounds is a larger percentage of the maximum strength of 1/2-inch diameter line than of 1-inch diameter line. Since nylon has a nonlinear load-elongation curve that increases steeply as load increases, that increase causes a sharp increase in K_0 for 1/2-inch diameter line whereas it is a much smaller increase for 1-inch diameter line. A more generalized form of figure 8 is shown in figure 11.

In order to determine the quasi-static spring constants, each sample was stored in water for 24 hours after the dynamic tests and then subjected to a slow (10 in/min) uni-directional loading and the load-strain curve recorded. These testing parameters were adopted because earlier tests showed that K_0 is affected by the rate of loading, the maximum load, and the elapsed time between removing the maximum load and recording the load-strain curve (i.e., recovery time). This is discussed in appendix D.

4.4.3 Load-Strain Curves

The load-strain curves and the comparison of them reveal much information about the quasi-static properties of materials and line constructions and the effect of the aging process on them.

The load-strain curves of nylon double-braided lines are a function of diameter (figure 12 and table 8). At a specific percentage of rated breaking strength, the corresponding strain of 1-inch diameter nylon double-braided line is approximately twice that of 1/2-inch diameter.

Nylon line of the 8-strand plaited and double-braid construction stretches 2-3 times more than polyester lines of the same construction and diameter (figures 13, 14 and table 8). It was also observed in section 4.4.1 that the dynamic elasticity of nylon lines is 2-3 times greater than that of polyester lines. 8-strand plaited lines stretch more than double-braid lines. For example, at 30% of rated breaking strength, nylon double-braided line and plaited line stretches approximately 15% and 25%, respectively. Polyester line of the same construction stretches 4% and 11%, respectively.

Exposure to the marine environment causes a fundamental change in the load-strain curve for all samples except polyester 8-strand plaited line. At all loads, the strain is greater than in new line at the same load (figures 13, 14 and table 9). This is reflected in an increase in the strain-at-failure discussed in section 4.4.4.

The load-strain curves show the fundamental difference in the elastic characteristics of nylon and polyester; that is, the load-strain relationship of nylon is quite nonlinear while in polyester it is rather linear. Since the load-strain curve for polyester is straight, the slope can be described by a constant, that is, the quasi-static spring constant discussed in section 4.4.2. That constant can be used in a computer model to calculate the elongation of a buoy mooring as a result of such quasi-static influences as current and wind. Since the load-strain relationship

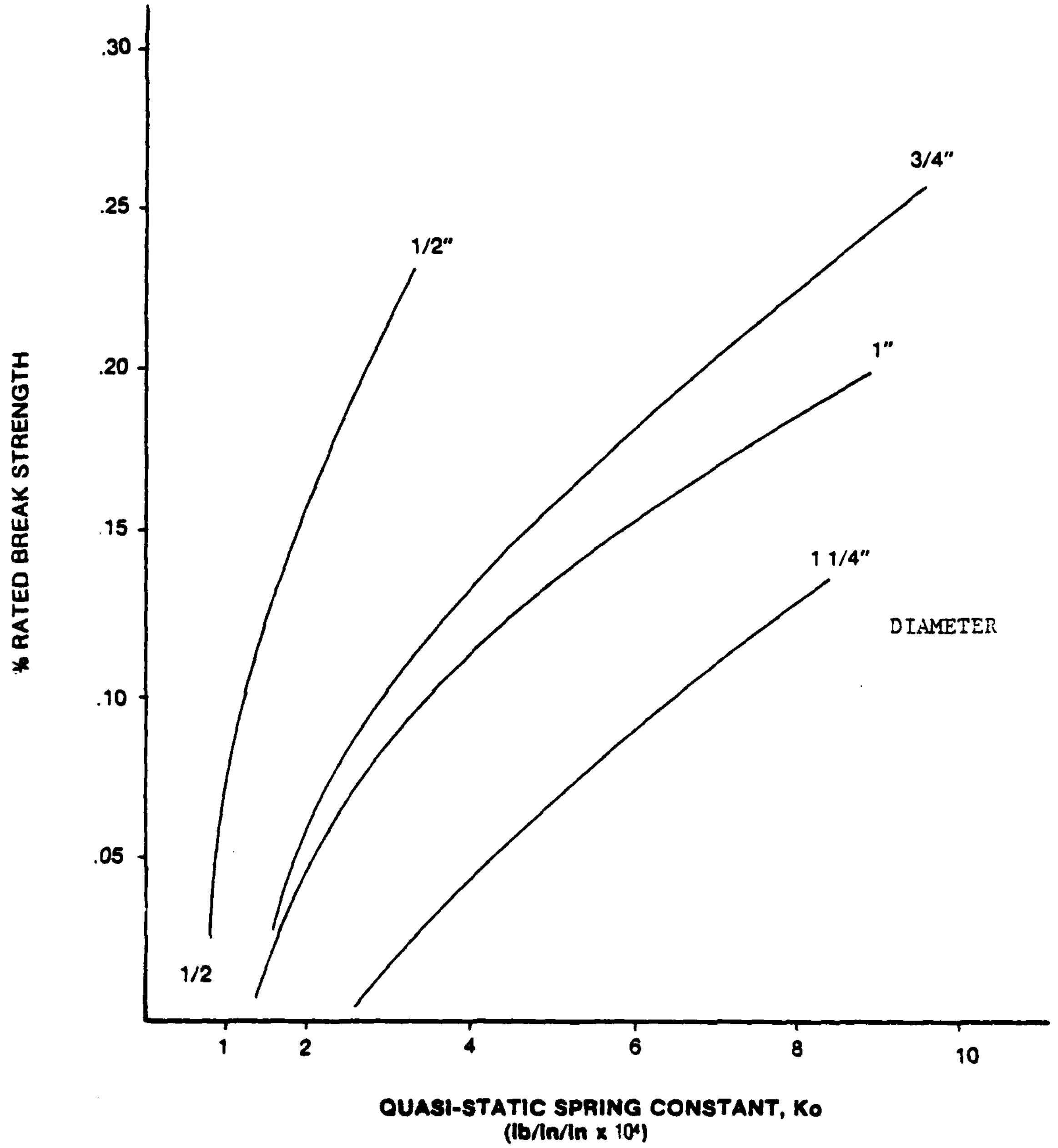


FIGURE 11

QUASI-STATIC SPRING CONSTANT, Ko, OF NYLON DOUBLE BRAID LINE, NEW, WET

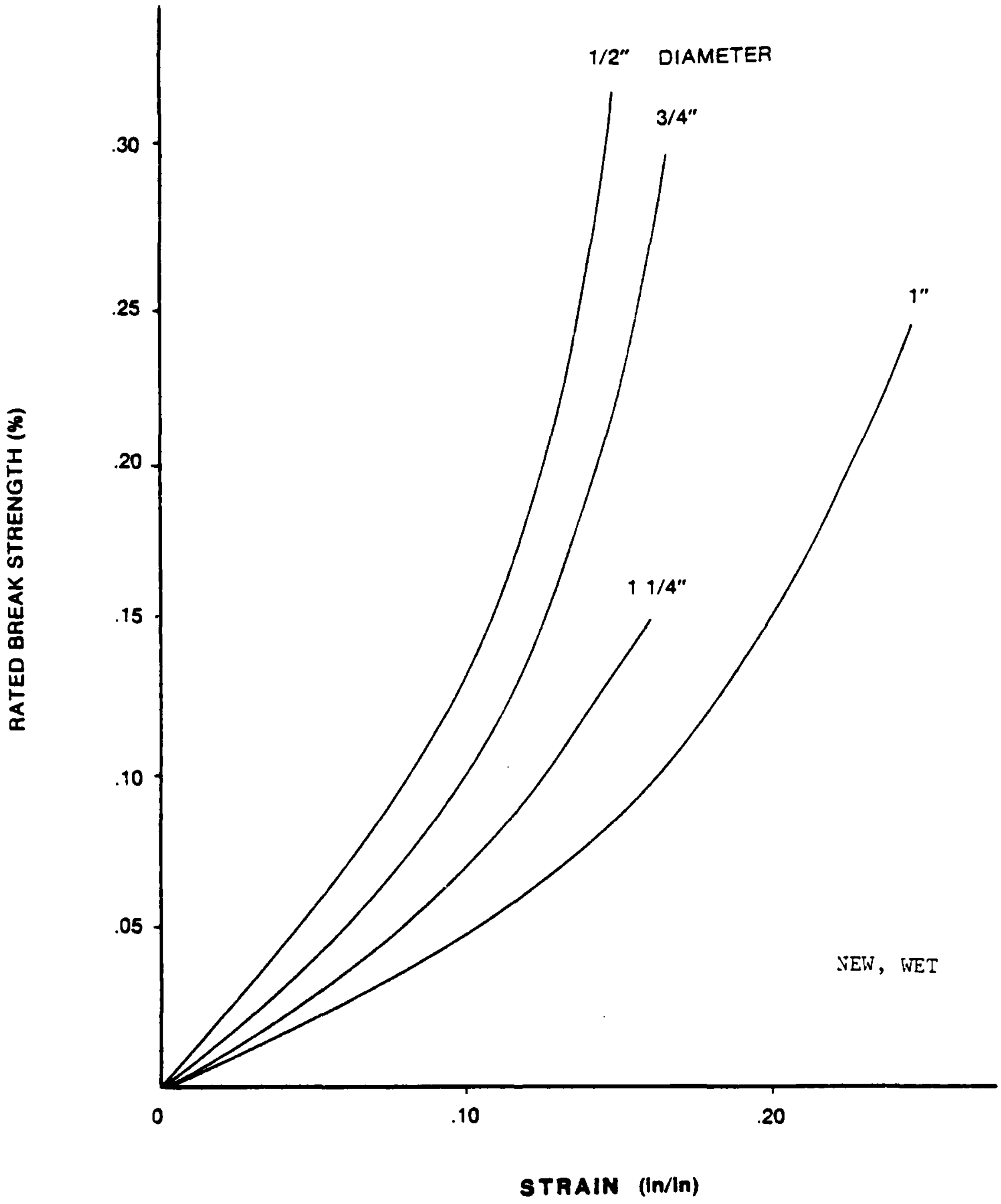


FIGURE 12

LOAD— STRAIN CURVES FOR NYLON DOUBLE BRAID LINE

TABLE 8

Load- STRAIN Equations For New, Wet Line.

$$\epsilon\left(\frac{in}{in}\right) = A + BT_m + CT_m^2 + DT_m^3$$

Material/Construction	Dia. (in)	$A \times 10^{-4}$	$B \times 10^{-4}$	$C \times 10^{-8}$	$D \times 10^{-12}$	Range of Usefulness (lbs)	Number of Samp.
Nylon Double Braid	1/2	-4.13	1.389	-3.906	3.795	1920	4
	3/4	33.04	.7428	-1.313	.896	5730	4
	1	17.12	.730	-.8606	.3995	8400	4
	1 1/4	4.83	.3862	-.343	.1398	7800	4
Nylon 8-Strand Plait.	1/2	368	1.694	-3.943	3.02	2363	9
	13/16	558	1.23	-2.33	2.275	17530	9
Polyester Double Braid	1/2	2.70	.2709	-.908	2.568	1920	3
Polyester 8-Strand Plaited	1/2	173.0	.417	.199	.4209	6690	3

T_m = Mean Tension

RBS = Rated Break Strength

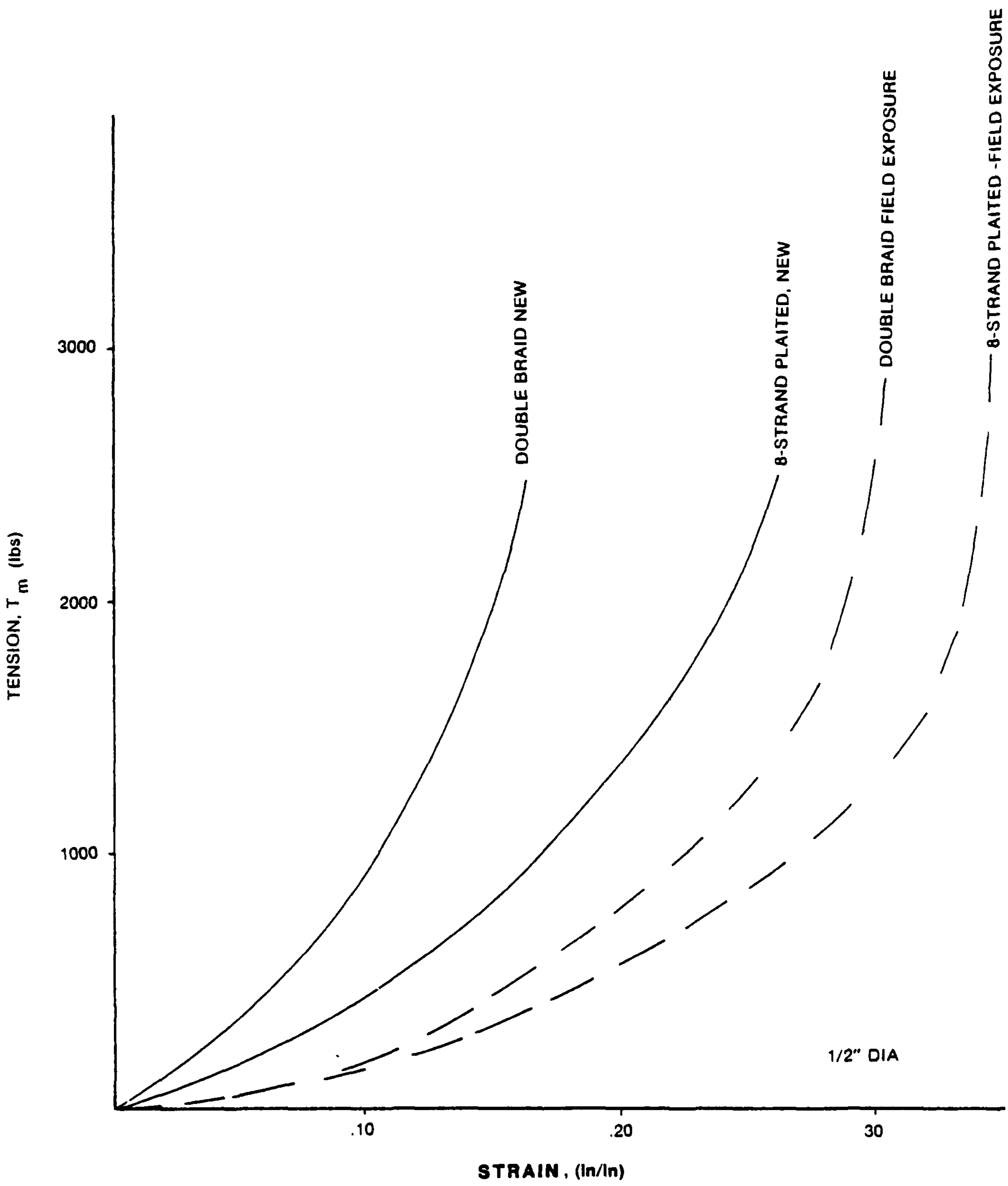


FIGURE 13

LOAD- STRAIN CURVES FOR WET NYLON LINE AFTER FIVE YEARS OF EXPOSURE TO THE MARINE ENVIRONMENT

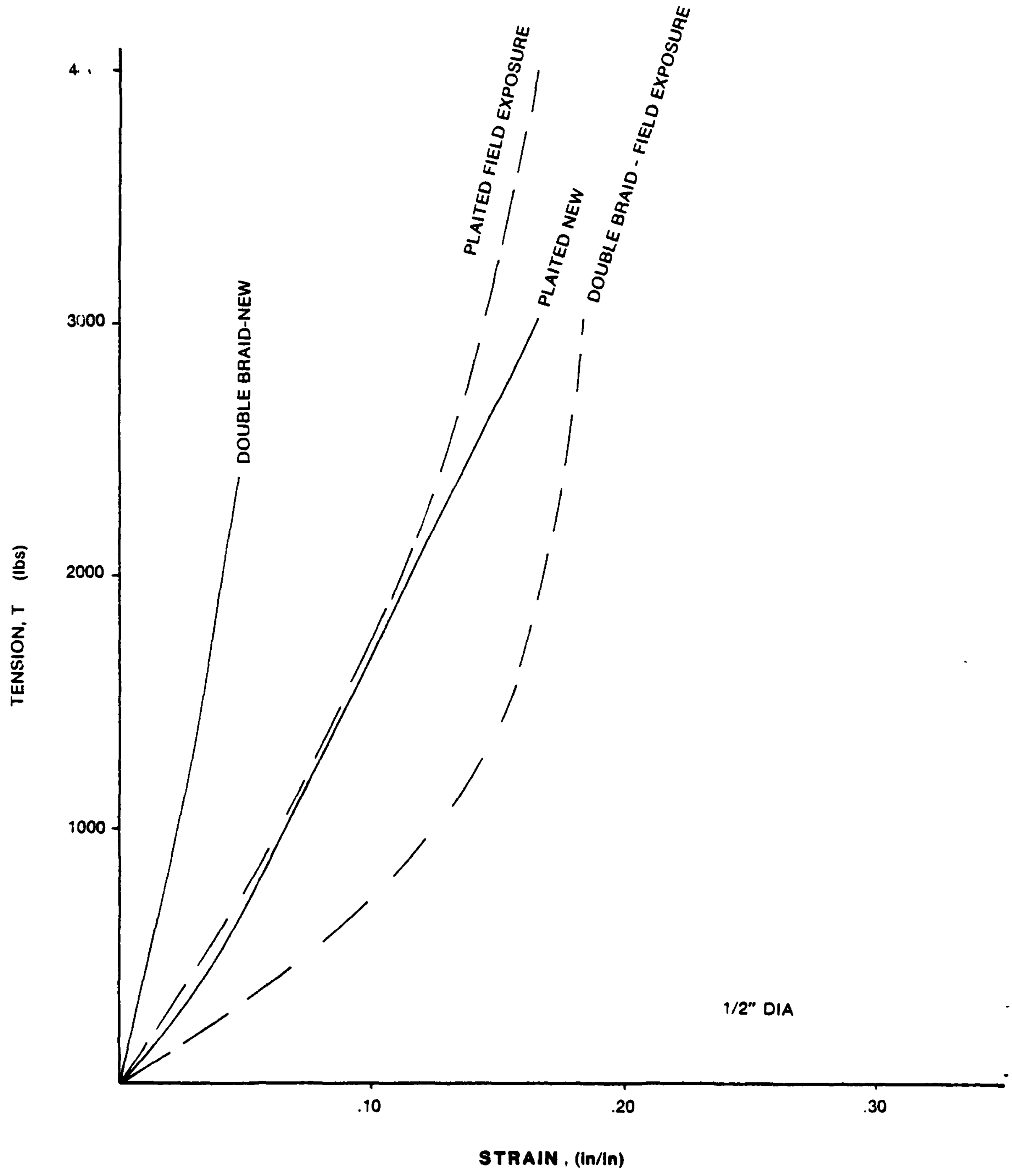


FIGURE 14

LOAD— STRAIN CURVES FOR WET POLYESTER LINE AFTER FOUR AND FIVE YEARS OF EXPOSURE TO THE MARINE ENVIRONMENT.

TABLE 9

Load- STRAIN Curves For Field Exposure Lines (1/2" Dia)

$\epsilon = A + BT_m + CT_m^2 + DT_m^3$

Material/ Construction	A x 10^{-4}	B x 10^{-4}	C x 10^{-8}	D x 10^{-12}	Range of Usefulness
Nylon Double Braid - New	4.13	1.389	-3.906	3.795	2400
Nylon Double Braid - 5 Years	740.0	2.014	-5.148	3.259	2700
Nylon 8-Strand Plaited - New	368	1.694	-3.943	3.02	2000
Nylon 8-Strand Plaited - 5 Years	597.9	3.08	-11.17	13.5 (1)	2000
Polyester Double Braid - New	2.70x	.2709	-.908	2.568	2500
Polyester Double Braid- 4 Years	Not Available				
Polyester Double Braid - 5 Years	28.53	1.848	-7.017	9.631	2000
Polyester 8-Strand Plait New	173.0	.477	.199	-.4209	6000
Polyester 8-Strand Plait 4 Years	-27.4	.8152	-1.542	1.461	2000

(1) One Sample Only

of nylon is quite nonlinear, a constant K_o value cannot be used for these calculations.

4.4.4 Tensile Strength and Strain-At-Failure

The tensile strength of nylon and polyester double-braided and 8-strand plaited line decreases by approximately 50% after four/five-years' exposure to the marine environment (table 10). The strain-at-failure increased approximately 50%. This is evident from the load-strain curves shown in figures 13 and 14.

Using the tensile strength data in table 10 and section 6.3.2, a tensile strength-versus-exposure curve can be constructed for 1/2-inch diameter polyester double-braided line (figure 15). It appears that strength declines in a linear manner over time of exposure to the marine environment. There is not sufficient data for the other field exposure samples to distinguish between the strength loss difference between four and five years of exposure. All data taken together, however, indicates that the lines shown in table 10 also lost approximately 50% of the original strength.

During the tensile testing of nylon double-braided line field exposure samples, it was observed that the core and cover bind at points along the line preventing distribution of load as the line elongates. The result is failure of the core at several points along the line before catastrophic failure occurs. In the test under discussion, as many as five breaks occurred in the core before the line failure occurred completely. Cutting the line at the point of core failure reveals an interesting situation. On one side of the cut, the core and cover are fused together and it is difficult to distinguish the core yarns from the cover yarns. On the other side of the cut, the core and cover are not attached and the cover can slide easily down the core. This phenomenon has been observed not only in field samples of 1/2-inch diameter line in this experiment, but also in inch and one-eighth nylon double-braided mooring line recovered from a NOAA Data Buoy Office NOMAD Buoy. That mooring was necked down at close intervals (approximately 12 to 18 inches) along the majority of the line length. Each neck area (approximately 4 to 6 inches long) was reduced to 7/8-inch diameter. Cutting the line through the neck area, the core and cover yarns were quite compressed. Exercising the end of the line eventually freed the core and cover yarns and restored flexibility. It has not been determined if heat damage was present.

4.4.5 Hysteresis, H

While apparent spring constant is probably the most important and easily understood design property of the synthetic line, hysteresis provides a good insight to the internal energy dissipation in the line caused by the damping characteristics of the material and friction between the strands.

The coefficients for the experimentally determined equation of hysteresis are shown in table 11. The magnitude of coefficients B_4 and B_7 and the negative sign of B_6 are highly significant. Coefficients B_4 and B_7 are the first- and second-order effect of load amplitude,

TABLE 10

Tensile Strength & Elongation
Field Exposure

1/2 Diameter

	NEW (1)				4 YEARS				5 YEARS				Change Compared to New Line			
													4 YEARS		5 YEARS	
Mat'l/Construction	Tensile Strength		Elongation at Failure		Tensile Strength		Elongation at Failure		Tensile Strength		Elongation at Failure		Tensile Strength Change		Elongation Change	
Polyester Double Braid	6400 (1)		.132		--		--		3241		.197		--	--	-49%	+51%
	16	473	16	.014	-	-	-	-	2		2	-				
Polyester 8-Strand	6690 (1)		.184		5096		.205		--		--		-23%	+11%	--	--
	10	335	10	.031	[illegible]	471	5	.037	-	-	-	-				
Nylon Double Braid	6512 (1)		.211		--		--		2783		.312		--	--	-57%	+47%
	20	455	20	.028		-	-	-	4	248	4	.021				
Nylon 8-Strand Plaited	7878		.284		3525		--		4416		.40		-55%	--	-44%	+40%
	13	461	13	.023	4	-	-	-	1	-	1	-				

(1) From Bitting, 1975.

Mean Value	
No. of Samples	Stand. Devia.

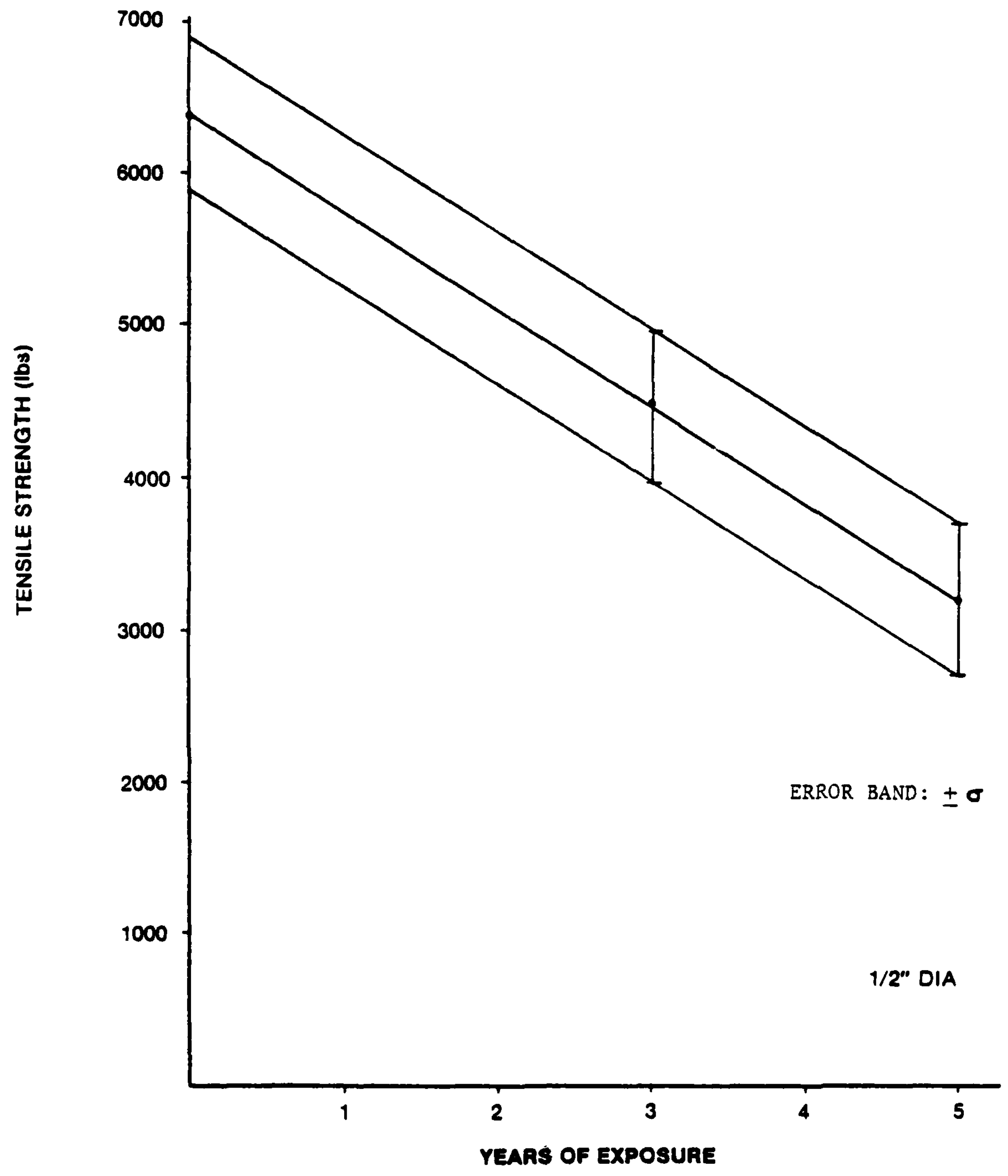


FIGURE 15

TENSILE STRENGTH REMAINING (WET) IN POLYESTER DOUBLE BRAID LINE AFTER EXPOSURE TO THE MARINE ENVIRONMENT.

TABLE 11

Hysteresis, H, Polynomial Equation Coefficients For New, Wet Line $\left(\frac{\text{lb-in}}{\text{in}}\right)$

FACTOR	COEFFICIENT	POLYESTER 1/2" DIA. 8-STRAND PLAIT	POLYESTER 1/2" DIA. DOUBLE BRAID	NYLON 8-STRAND PLAIT (1/2")	NYLON DOUBLE BRAID (DIA.) 1/2"	NYLON DOUBLE BRAID (DIA.) 3/4"	NYLON DOUBLE BRAID (DIA.) 1"	NYLON DOUBLE BRAID (DIA.) 1 1/4"
MEAN	B_1	1.392	3.593	3.10	3.08	8.23	30.92	20.567
f^2	B_2	.678	-.917	.572	.43	1.329	2.073	2.938
T_m^2	B_3	.251	.738	.638	1.788	8.489	9.743	7.98
ΔT^2	B_4	.366	.339	1.070	.661	1.484	6.670	6.26
f	B_5	.220	-.012	.026	.162	-.082	4.599	3.79
T_m	B_6	-1.244	1.132	-2.351	-3.817	12.793	-19.37	-16.43
ΔT	B_7	1.521	-.207	3.600	4.008	11.188	26.09	20.84
f, T_m	B_8	-.323	-.100	.435	-.567	-1.568	-3.79	-7.22
$f, \Delta T$	B_9	.107	.040	.069	.069	-1.158	4.02	1.138
$T_m \Delta T$	B_{10}	.070	-.596	-1.473	-2.764	-9.468	-8.04	-11.363
	r^2	.907	.905	.990	.992	.974	.995	.994
	F-STAT.	3.87	3.805	40.09	48.39	15.268	85.211	62.691
	F-CRIT.	3.48	3.48	3.48	3.48	3.48	3.48	3.48
RANGE OF USEFULNESS OF EQUATION:	f	1 - 5						
	T_m	792 - 1980	768 - 1920	691 - 1728	768 - 1920	2292 - 5730	3360 - 7392	3300 - 7392
	ΔT	±330 - ±792	±320 - ±768	±288 - ±691	±320 - ±768	±955 - ±2292	±1680-±3360	±1680-±3380

ΔT. Since these coefficients are much greater than the others, they have a much larger effect on H. The negative sign of coefficient B_6 indicates that mean load has an inverse effect on hysteresis; that is, hysteresis is high at low mean loads. The general observation is: hysteresis is high at (a) high values of load amplitude, and (b) low values of mean load. These conditions tend toward the case where the load in the sample drops to zero during each cycle. The effect of mean load and load amplitude is observed in figure 16. For a frequency of 0.1 Hz, points on the response surface represent the combined effect of mean load and load amplitude on the hysteresis of nylon plaited line.

The data in table 11 also indicate that frequency has very little effect on hysteresis. This is a major departure from the theory represented in equation (4) and supports the preliminary conclusion drawn from the screening test (appendix A) and work by Paquette and Henderson (1965).

The factor combination of low mean load and high load amplitude that cause high hysteresis are the same combination that is associated with failure due to snap loading (Bunsell (1971) and section 5.0). As explained in section 5.0, the failure of the line in that situation is associated with a zero minimum load during a load cycle and appears not to be associated with heat generation in the line. No quantitative heat measurements were made to explore this situation, however.

The regression equation coefficients (equation 5) for the hysteresis, H, of nylon and polyester field-exposure samples are shown in tables 12 and 13, respectively. The general trend is toward an increase in hysteresis during exposure to the marine environment. The hysteresis of nylon double-braided line increases 81 percent and polyester double-braided line increases 78 percent during exposure. The other material/construction combinations are shown in tables 12 and 13 for purposes of documentation. Because of the small sample size, no inference will be drawn.

4.4.6 Dissipation Spring Constant, K_1

The coefficients for the regression equation for K_1 are shown in table 14. These coefficients have no significance other than that they produce a K_1 that, with a proper value of K_0 and τ, will yield K_{ap} (as discussed in section 4.2). It is interesting to note that the coefficients of mean load (a static factor), coefficients B_3 and B_6 in table 14, are much greater than the coefficients of frequency and load amplitude (both dynamic factors) indicating that those dynamic factors have little effect on K_1. This is consistent with theory because K_1, being a spring element, should not be rate dependent even though it operates in consort with τ to simulate the dynamic properties of the line. The dissipation spring constants, K_1, generally increases (tables 16 and 15) with exposure to the marine environment.

4.4.7 Characteristic Relaxation Time, τ

The characteristic relaxation time, τ, combined with the spring constant, K_1, describes the energy dissipation hysteresis property of the synthetic line. At this time, the value of τ has no other quantitative use other than its use in equations (1) and (4). However, the trend in

FREQUENCY (f): 0.1 Hz
MEAN LOAD (T_m): 12% RBS — 30% RBS
LOAD AMPLITUDE (ΔT): ±5% RBS — ±12% RBS
1/2" DIAMETER, NEW, WET

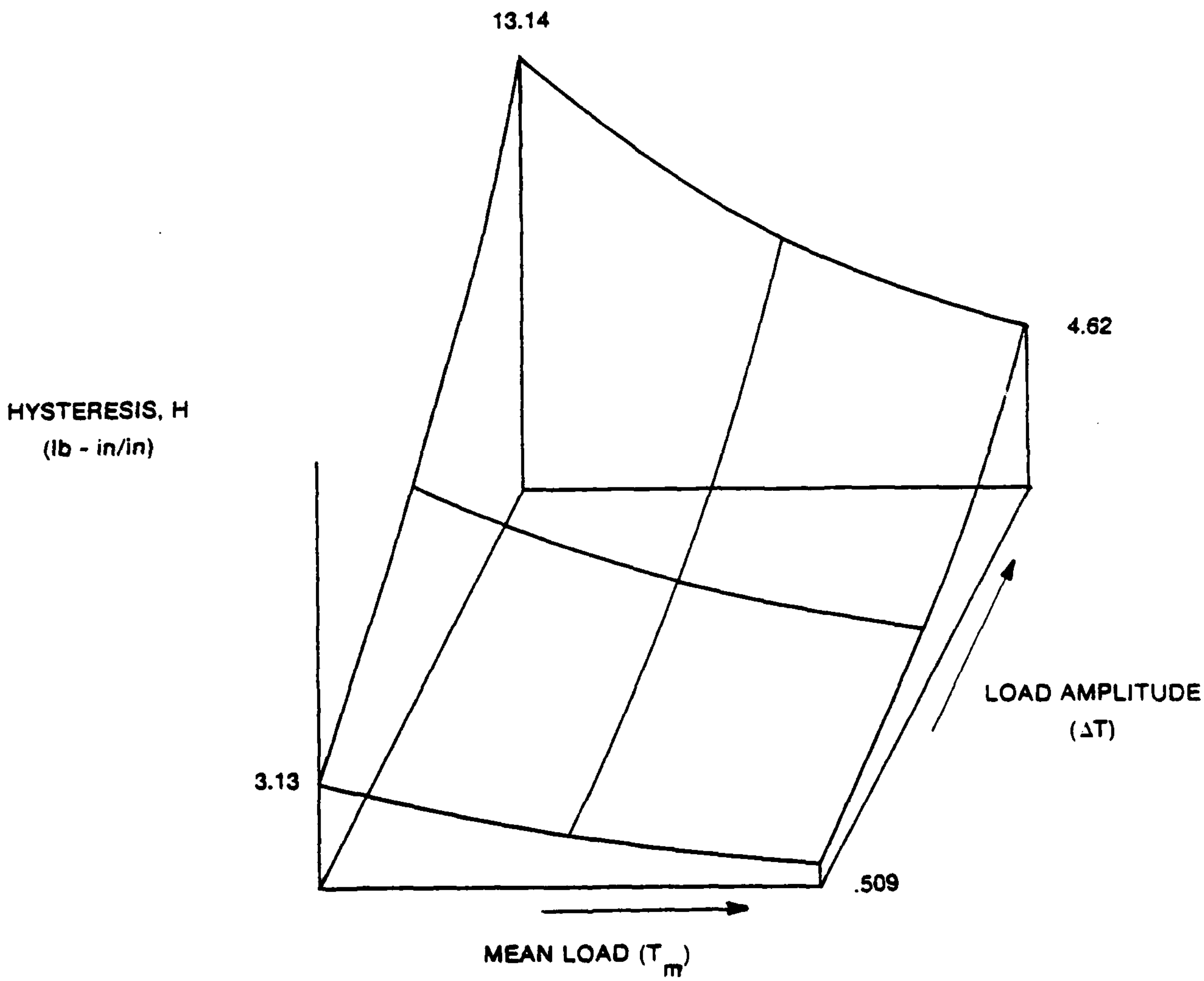


FIGURE 16

HYSTERESIS RESPONSE SURFACE — NYLON 8-STRAND PLAITED LINE (NEW)

TABLE 12

Nylon Line Field Exposure Polynomial Equation Coefficients For Hysteresis, H(1/2" Dia Line) $\left(\frac{\text{lb-in}}{\text{in}}\right)$

FACTOR	POLYNOMIAL EQUATION COEFFICIENT	NYLON PLAITED NEW	NYLON PLAITED FIELD EXPOSURE 4 YEAR (1)	NYLON PLAITED FIELD EXPOSURE 5 YEAR (1)	NYLON DOUBLE-BRAID NEW	NYLON DOUBLE-BRAID 5 YEAR
MEAN	B_1	3.100	1.400	4.32	3.080	5.587
f^2	B_2	.572	-.531	2.188	.43	.658
T_m^2	B_3	.638	.819	3.84	1.788	.375
ΔT^2	B_4	1.070	.281	-.642	.661	.075
f	B_5	.026	-.431	.918	.162	-.160
T_m	B_6	-2.351	-1.019	-3.235	-3.817	-3.848
ΔT	B_7	3.600	1.350	4.798	4.008	3.568
f, T_m	B_8	.435	.513	.712	-.567	.090
$f, \Delta T$	B_9	.069	-.350	-.372	.069	-.310
$T_m, \Delta T$	B_{10}	-1.473	-.700	-3.683	-2.764	-2.438
	r^2	.990	.936	.923	.992	.983
	F-STAT	40.09	5.827	4.811	48.39	32.833
	F-CRIT	3.48	3.48	3.48	3.48	3.48
	No. of Lines Tested	3	2	2	3	4
	Change in H					81%
USEFUL RANGE OF EQUATION:	f (Hz)	.1 - .5				
	T_m(lbs)	691 - 1728			768 - 1920	
	ΔT(lbs)	$\pm$288 - $\pm$691			$\pm$320 - $\pm$768	

(1) Limited data available because of premature failure during dynamic test or loss during field deployment. No analysis performed on this data.

TABLE 13

Polyester Line Field Exposure Polynomial Equation Coefficients For Hysteresis, H(1/2" Dia Line)

$\left(\frac{lb-in}{in}\right)$

FACTOR	POLYNOMIAL EQUATION COEFFICIENT	POLYESTER PLAITED NEW	POLYESTER PLAITED FIELD EXPOSURE 4 YEAR	POLYESTER DOUBLE-BRAID NEW	POLYESTER DOUBLE-BRAID 4 YEAR	POLYESTER DOUBLE-BRAID EXPOSURE 5 YEAR
MEAN	B_1	1.392	.213	1.20	2.110	2.173
f^2	B_2	.678	.081	.052	-.424	.341
T_m^2	B_3	.251	.611	.078	.474	.751
ΔT^2	B_4	.366	1.153	.322	1.026	.591
f	B_5	.220	.069	-.324	.251	-.068
T_m	B_6	-1.244	-.769	-.631	-1.595	-1.083
ΔT	B_7	1.521	1.310	1.245	2.46	2.257
f, T_m	B_8	-.323	.215	.079	-.040	-.315
$f, \Delta T$	B_9	.107	-.013	-.448	.128	-.275
$T_m, \Delta T$	B_{10}	-.070	-.953	-.421	-1.335	-1.020
	r^2	.907	.959	.976	.983	.990
	F-STAT	3.87	9.39	16.47	23.64	41.4
	F-CRIT	3.48	3.48	3.48	3.48	3.48
	Number of Lines Tested	4	2	3	4	2
	Change in H					78%
USEFUL RANGE OF EQUATION:	f (Hz)	.1 - .5				
	T_m (lbs)	792 - 1980		840 - 2100		
	ΔT (lbs)	±330 - ±792		±350 - ±840		

(1) Limited data available because of premature failure during dynamic test or loss during field deployment. No analysis performed on this data.

TABLE 14

Dissipation Spring Constant, K_1 Polynomial Equation Coefficients Of New, Wet Line

($lb/in/in \times 10^4$)

FACTOR	POLYNOMIAL EQUATION COEFFICIENT	POLYESTER 1/2" Dia. DIAMETER		NYLON 8-STRAND PLAIT 1/2" Dia.	NYLON DOUBLE BRAID (DIAMETER)			
		8-Strand Plait	Double Braid		1/2"	3/4"	1"	1 1/4"
MEAN	B_1	4.353	3.593	1.855	1.699	4.463	8.807	13.413
f^2	B_2	.010	-.917	-.112	.033	.190	-.865	2.171
T_m^2	B_3	.360	.738	-.108	-.398	1.21	-.342	-1.499
ΔT^2	B_4	-.008	.339	-.087	-.122	.075	.703	.633
f	B_5	.364	-.012	.021	.147	.070	-.575	-.669
T_m	B_6	1.589	1.132	.756	.532	3.138	4.168	4.816
ΔT	B_7	-.070	-.207	-.236	-.118	-1.20	-2.419	-1.76
$f\ T_m$	B_8	.413	-.100	.121	.027	.053	-.415	2.535
$f, \Delta T$	B_9	.040	.040	-.046	0.0	.297	-.405	1.802
$T_m \cdot \Delta T$	B_{10}	-.210	-.576	.014	.052	-.033	-1.708	-.673
	r^2	.967	.905	.993	.969	.987	.968	.878
	F-STAT	11.783	3.805	60.264	12.321	30.597	12.281	2.814
	F-CRIT	3.48	3.48	3.48	3.48	3.48	3.48	3.48
RANGE OF USEFULNESS OF EQUATION	f	.1 - .5						
	T_m	792 - 1980	840 - 2100	691 - 1728	768 - 1920	2292 - 5730	3360 - 7392	3360 - 7392
	ΔT	±330 - ±792	±350 - ±840	±288 - ±691	±320 - ±768	±955-±2292	±1680-±3380	±1680-±3360

TABLE 15

Nylon Line Field Exposure Polynomial Equation Coefficients For Dissipation Spring Constant, K_1 (½" Dia Line)

($lb/in/in \times 10^4$)

	Polynomial Equation Coefficient	Nylon Plaited New	Nylon Plaited Field Exposure 4 Year	Nylon Plaited Exposure 5 Year	Nylon Double-Braid New	Nylon Double-Braid 5 Year
MEAN	B_1	1.855		2.785	1.699	6.360
f^2	B_2	-.112		.171	.033	1.066
T_m^2	B_3	-.168		.404	-.398	.854
ΔT^2	B_4	-.087		.222	-.122	-.409
f	B_5	.021		.298	.147	-.631
T_m	B_6	.756		2.292	.532	3.543
ΔT	B_7	-.236		-.647	-.118	-1.329
f, T_m	B_8	.121		.260	.027	-2.865
$f, \Delta T$	B_9	-.046		.411	0.0	1.453
$T_m, \Delta T$	B_{10}	.014		.778	.052	.205
	r^2	.993		.961	.969	.988
	F-STAT	60.264		9.75	12.321	32.833
	F-CRIT	3.48		3.48	3.48	3.48
USEFUL RANGE OF EQUATION:	f (Hz)	.1 - .5				
	T_m (lbs)	691 - 1728			768 - 1920	
	ΔT (lbs)	$\pm$288 - $\pm$691			$\pm$320 - $\pm$788	

TABLE 16

Polyester Line Field Exposure Polynomial Equation Coefficients For Dissipation Spring Constant, K_1(½" Dia Line)

($lb/in/in \times 10^4$)

FACTOR	POLYNOMIAL EQUATION COEFFICIENT	POLYESTER 8-STRAND PLAITED NEW	POLYESTER 8-STRAND PLAITED FIELD EXPOSURE	POLYESTER DOUBLE-BRAID NEW	POLYESTER DOUBLE-BRAID 4 YEAR	POLYESTER DOUBLE-BRAID 5 YEAR
MEAN	B_1	4.353	Results	3.593	Results	8.533
f^2	B_2	.010	Not	-.917	Not	-.808
T_m^2	B_3	.360	Available	.738	Available	.398
ΔT^2	B_4	-.008		.339		.917
f	B_5	.364		-.002		.019
T_m	B_6	1.589		1.132		2.765
ΔT	B_7	-.070		-.207		-1.674
f, T_m	B_8	.413		-.100		.410
$f, \Delta T$	B_9	.040		.040		.638
$T_m \Delta T$	B_{10}	-.210		-.596		-.998
	r^2	.967		.905		.916
	F-STAT	11.783		3.805		4.36
	F-CRIT	3.48		3.48		3.48
USEFUL RANGE OF EQUATION:	f (Hz)	.1 - .5				
	T_m (lbs)	792 - 1980		840 - 2100		
	ΔT (lbs)	± 330 - ± 792		± 350 - ± 840		

characteristic relaxation time τ is loosely linked to a trend in hysteresis and discussing it adds to the intuitive understanding of the dissipation mechanisms of synthetic line.

The polynomial equation coefficients for τ are shown in table 17. Coefficient B_1 is the mean value of τ and can be thought of as typical of any particular line. It is observed that Coefficient B_1 values (table 17) for nylon are relatively close regardless of the diameter and construction. This suggests that τ is truly characteristic of the nylon material. (NOTE: It is noted that the coefficients for 1/2-inch diameter nylon double-braided line do not pass the goodness of fit test at the 95 percent confidence limit since F-STAT is less than F-CRIT and, therefore, are not considered with the other data.) The first- and second-order effects of frequency are very strong; mean load and load amplitude are significant factors as well. The fact that τ is a strong function of frequency is intuitively correct because τ is the measure of the dashpot which is the dynamic element in the three-parameter model. Being a function of frequency, mean load, and load amplitude is consistent with preliminary observations of the screening experiment (appendix A); that is, τ is a function of several factors and there are strong interactions among the factors. Coefficients B_8 through B_{10} (the interaction coefficients) in table 17 are also very large with respect to the mean value (B_1).

An interesting insight is gained by comparing the sign of the mean load (B_6) and load amplitude (B_7) term for τ and H. For H, B_6 is negative and B_7 is positive, and for τ, B_6 is positive and B_7 is negative. This inverse trend is apparent by comparing figure 19 and figure 17. For a given frequency, a high value of hysteresis is accompanied by a low value of τ and vice-versa. It may be interpreted qualitatively by recalling the mechanical analog (figure 1). If the dashpot has a slow relaxation time (i.e., high value of τ), the dashpot will not have sufficient time to react and dissipate energy (i.e., low hysteresis). Conversely, if the dashpot has a fast reaction time (low value of τ), it will react and dissipate energy. This trend can be observed in different materials as well. Comparing the mean values of tables 11 and 17, nylon exhibits a relatively high value of H and relatively low value of τ and polyester exhibits a relatively low value of H and a high value of τ. The characteristic time constants of the field exposure samples are shown in tables 18 and 19.

4.4.8 Conclusions

1. The apparent spring constant, K_{ap}, is typically 3-4 times greater than the quasi-static spring constant.

2. The apparent spring constant of nylon double-braided line increases approximately 99% after 5 years exposure to the marine environment. Polyester 8-strand plaited line increased in stiffness approximately 30% over a similar time period.

3. The quasi-static spring constant of nylon is highly nonlinear and should not be used for calculating the elongation under static conditions. The load-strain curve should be used for that.

TABLE 17

Characteristic Relation Time, τ, Polynomial Equation Coefficients Of New, Wet Line

(SECONDS)

FACTOR	POLYNOMIAL EQUATION COEFFICIENT	POLYESTER 1/2" DIA. 8-STRAND PLAIT	POLYESTER 1/2" DIA. DOUBLE BRAID	NYLON 8-STRAND PLAITED (1/2" DIA.)	NYLON DOUBLE BRAID (DIA.) 1/2"	NYLON DOUBLE BRAID (DIA.) 3/4"	NYLON DOUBLE BRAID (DIA.) 1"	NYLON DOUBLE BRAID (DIA.) 1 1/4"
MEAN	B_1	4.007	1.488	2.057	2.272	1.643	1.560	1.643
f^2	B_2	4.885	1.169	2.173	.679	.755	1.221	.978
T_m^2	B_3	.761	.260	-.272	-.057	.92	.0264	-.194
ΔT^2	B_4	1.710	.098	.833	3.229	-.365	-.459	-.024
f	B_5	-7.708	-1.278	-3.523	-2.791	-1.545	-1.591	-1.718
T_m	B_6	4.576	1.751	1.235	2.568	1.245	.333	.469
ΔT	B_7	-2.75	-.823	-1.243	.455	-.510	-.094	-.229
f, T_m	B_8	-5.908	-1.151	-1.173	.111	-.742	.555	-.438
$f, \Delta T$	B_9	3.482	.763	1.458	2.318	.198	-.003	.178
$T_m \Delta T$	B_{10}	-2.823	-.481	-.593	4.648	-.123	.030	.075
	r^2	.906	.972	.968	.650	.934	.989	.980
	F-STAT	3.84	13.639	12.12	.742	5.688	34.62	19.142
	F-CRIT	3.48	3.48	3.48	3.48	3.48	3.48	3.48
USEFUL RANGE OF EQUATION:	f (Hz)	.1 - .5						
	T_m (lbs)	792-1980	840-2100	691-1728	768-1920	2292-5730	3360-7392	3360-7392
	ΔT (lbs)	±330-±792	±350-±840	±288-±691	±320-±768	±955-±2292	±1680-±3360	±1680-±3360

TABLE 18

Nylon Line Field Exposure Polynomial Equation Coefficients For Characteristic Relaxation Time, τ (1/2" Dia Line)

(SEBONDS)

FACTOR	POLYNOMIAL EQUATION COEFFICIENT	NYLON PLAITED NEW	NYLON PLAITED FIELD EXPOSURE 4 YEAR	NYLON PLAITED 5 YEAR (1)	NYLON DOUBLE-BRAID NEW	NYLON DOUBLE-BRAID 5 YEAR
MEAN	B_1	2.057		1.825	2.272	1.130
f^2	B_2	2.173		1.284	.679	1.077
T_m^2	B_3	-.272		.730	-.057	-.168
ΔT^2	B_4	.833		-.414	3.229	.320
f	B_5	-3.523		-1.708	-2.791	-1.056
T_m	B_6	1.235		.881	2.583	.048
ΔT	B_7	-1.243		.073	.455	.460
f, T_m	B_8	-1.173		-.740	.111	.155
$f, \Delta T$	B_9	1.458		.668	2.318	.618
$T_m, \Delta T$	B_{10}	-.593		.807	4.648	-.032
	r^2	.968		.926	.650 (1)	.981
	F-STAT	12.12		5.017	.742	20.857
	F-CRIT	3.48		3.48	3.48	3.48
USEFUL RANGE OF EQUATION:	f (Hz)	.1 - .5				
	T_m (lbs)	691 - 1728			768 - 1920	
	ΔT (lbs)	$\pm$288 - $\pm$691			$\pm$320 - $\pm$768	

(1) Does not pass goodness of fit test at 95% confidence.

TABLE 19

Polyester Line Field Exposure Polynomial Equation Coefficients For Characteristic Relaxation Time, τ (1/2" Dia Line)

(SECONDS)

FACTOR	POLYNOMIAL EQUATION COEFFICIENT	POLYESTER 8-STRAND PLAITED NEW	POLYESTER 8-STRAND PLAITED FIELD EXPOSURE	POLYESTER DOUBLE BRAID NEW (1)	POLYESTER 4-YEAR DOUBLE BRAID	POLYESTER DOUBLE BRAID 5 YEAR
MEAN	B_1	4.007	RESULTS	1.488	RESULTS	2.233
f^2	B_2	4.885	NOT	1.169	NOT	1.161
$T_m{}^2$	B_3	.761	AVAILABLE	.266	AVAILABLE	-.368
ΔT^2	B_4	1.710		.098		-.513
f	B_5	-7.708		-1.278		-1.94
T_m	B_6	4.576		1.751		-.411
ΔT	B_7	-2.75		-.823		.298
f, T_m	B_8	-5.908		-1.151		.648
$f, \Delta T$	B_9	3.482		.763		-.408
$T_m \cdot \Delta T$	B_{10}	-2.823		-.481		.388
	r^2	.906		.972		.954
	F-STAT	3.84		13.639		8.37
	F-CRIT	3.48		3.48		3.48
USEFUL RANGE OF EQUATION:	f (Hz)	.1 - .5				
	T_m (lbs)	792 - 1980		840 - 2100		
	ΔT (lbs)	+330 - +792		+350 - +840		

FREQUENCY (f): 0.1 Hz

MEAN LOAD (T_m): 12% RBS - 30% RBS

LOAD AMPLITUDE (ΔT): $\pm 5\%$ RBS - $\pm 12\%$ RBS

1 /2" DIAMETER, NEW, WET

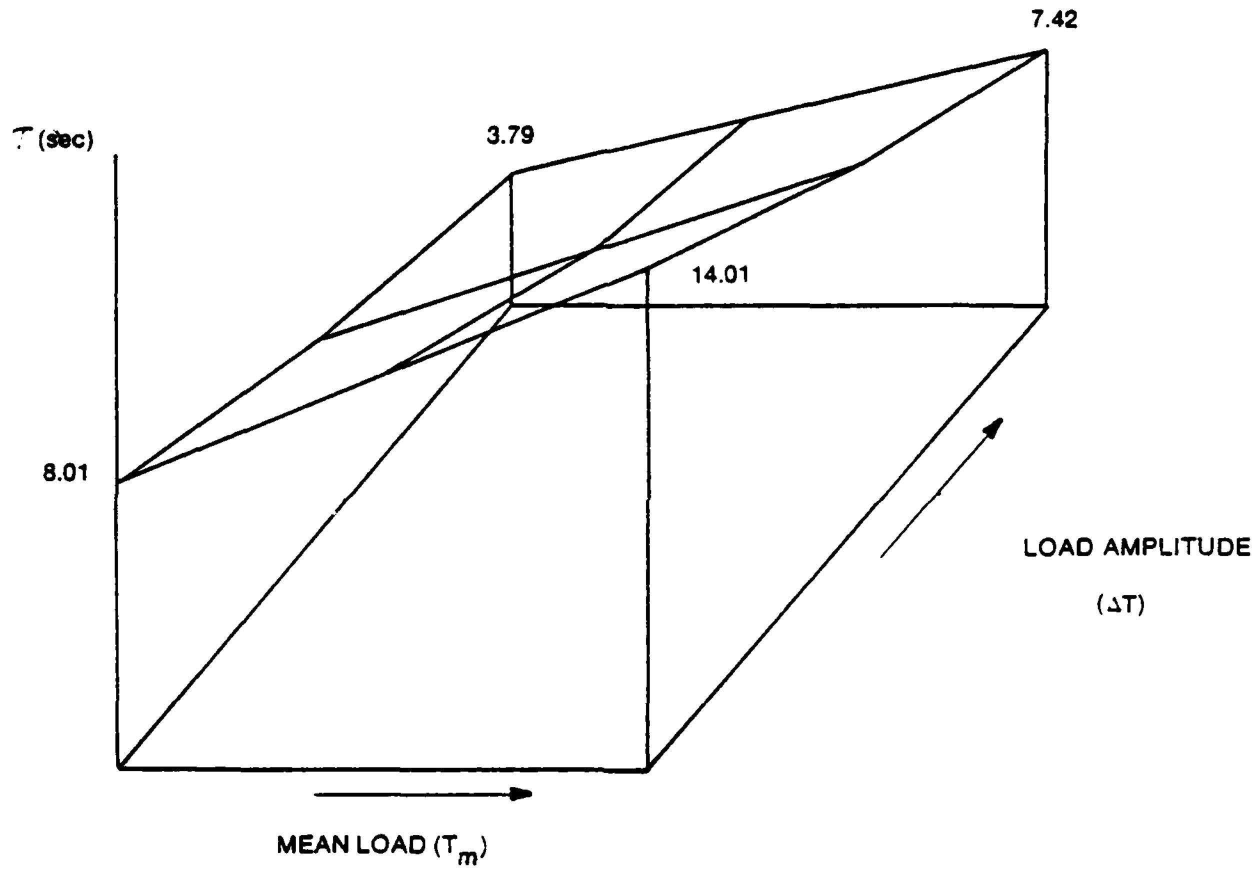


FIGURE 17

CHARACTERISTIC RELAXATION TIME, τ, RESPONSE SURFACE - NYLON 8-STRAND PLAITED LINE (NEW)

4. The quasi-static spring constant of nylon and polyester line increases due to exposure to the marine environment. The quasi-static spring constant of polyester line becomes nonlinear as a result of exposure to the marine environment.

5. The load-strain curve of nylon double-braided line is a function of diameter.

6. Nylon double braided and 8-strand plaited line stretch 2-3 times more than polyester line of the same construction and diameter.

7. The tensile strength of nylon and polyester double-braided and 8-strand plaited line decreases by approximately 50% after 4-5 years of exposure to the marine environment.

8. The strain-at-failure of nylon and polyester double braided and 8-strand plaited lines increases by approximately 50% after 4-5 years in the marine environment.

5.0 FATIGUE FAILURE OF NYLON LINE

5.1 Objective And Background

The objective of this test is to determine the reduction in tensile strength caused by cyclic loading in which the minimum load during a cycle is zero.

Previous laboratory tests (appendix A) show that cyclic loading up to 62% of the rated breaking strength does not cause a significant change in the tensile strength of nylon line if the load in the sample never reaches zero. Work by other investigators (Bunsell, 1971) indicates that the disappearance of the load during the load cycle is a necessary condition for the fatigue of nylon filaments. Since this phenomenon occurs in filaments and since buoy moorings are expected to be slack at some point during the loading cycle, a set of laboratory tests were conducted to investigate the phenomenon of stranded synthetic fiber line.

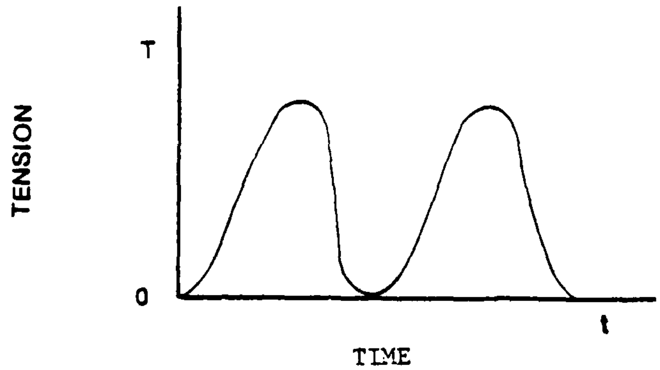
The term "snap load" refers to the fact that the line goes slack (but does not necessarily bend) during the loading cycle; this does not necessarily refer to the rate of loading. Work by Bunsell shows that when the minimum load in a cycle is zero (figure 18(a)), a characteristic "tail" is evident on the end of the filament (figure 18(b)) when it fails. This tail is caused by a combination of the stress field in the filament and the compressive properties of nylon. A tensile failure (figure 18(c)) shows a characteristic flat end with a notch on the side where plastic deformation occurred. This characteristic failure mode can be observed under a microscope in individual filaments. In stranded constructions, the abrasion of one filament on the other, the heat generated during cycling, the torsion effect of the yarns wrapped around each other, and backlash occurring during failure all alter the filament's appearance when these factors operate singly or in consort. In addition to the problem of these factors masking fatigue failures, the sheer number of filaments in the end of a broken line increases the difficulty of identifying fatigue failures.

5.2 Test Plan

Samples of 1/2-inch diameter nylon 8-strand plaited line (2 feet in length) were cyclically loaded between zero and some percentage of rated breaking strength at a frequency of 0.5 Hz. All samples were tested submerged in water on the cyclic/tensile test machine described in appendix B. Each sample was cycled until it parted; the number of cycles-to-failure was then recorded. The maximum load of the first test was approximately 70% of rated breaking strength. The maximum load was reduced in subsequent tests until a load level was reached at which failure did not occur by 200,000 cycles. At least three samples were tested at each maximum load level.

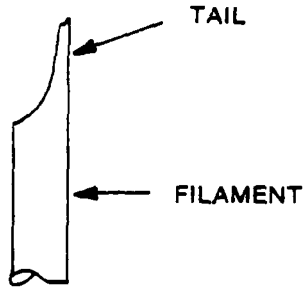
5.3 Results

The results of the snap load tests are shown in figure 19. The solid line connects the mean values of cycles-to-failure at each maximum load level. The mean value of the lowest maximum load level at which failure occurred is connected by a dash line to the load level at which failure did not occur by 200,000 cycles. It can be seen that at maximum loads



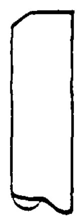
(a)

"SNAP LOAD" LOADING CONDITION (TENSION/NO TENSION)



(b)

CHARACTERISTIC FATIGUE FAILURE MODE OF A NYLON FILAMENT



(c)

CHARACTERISTIC TENSILE FAILURE OF A NYLON FILAMENT

FIGURE 18

FATIGUE MODES

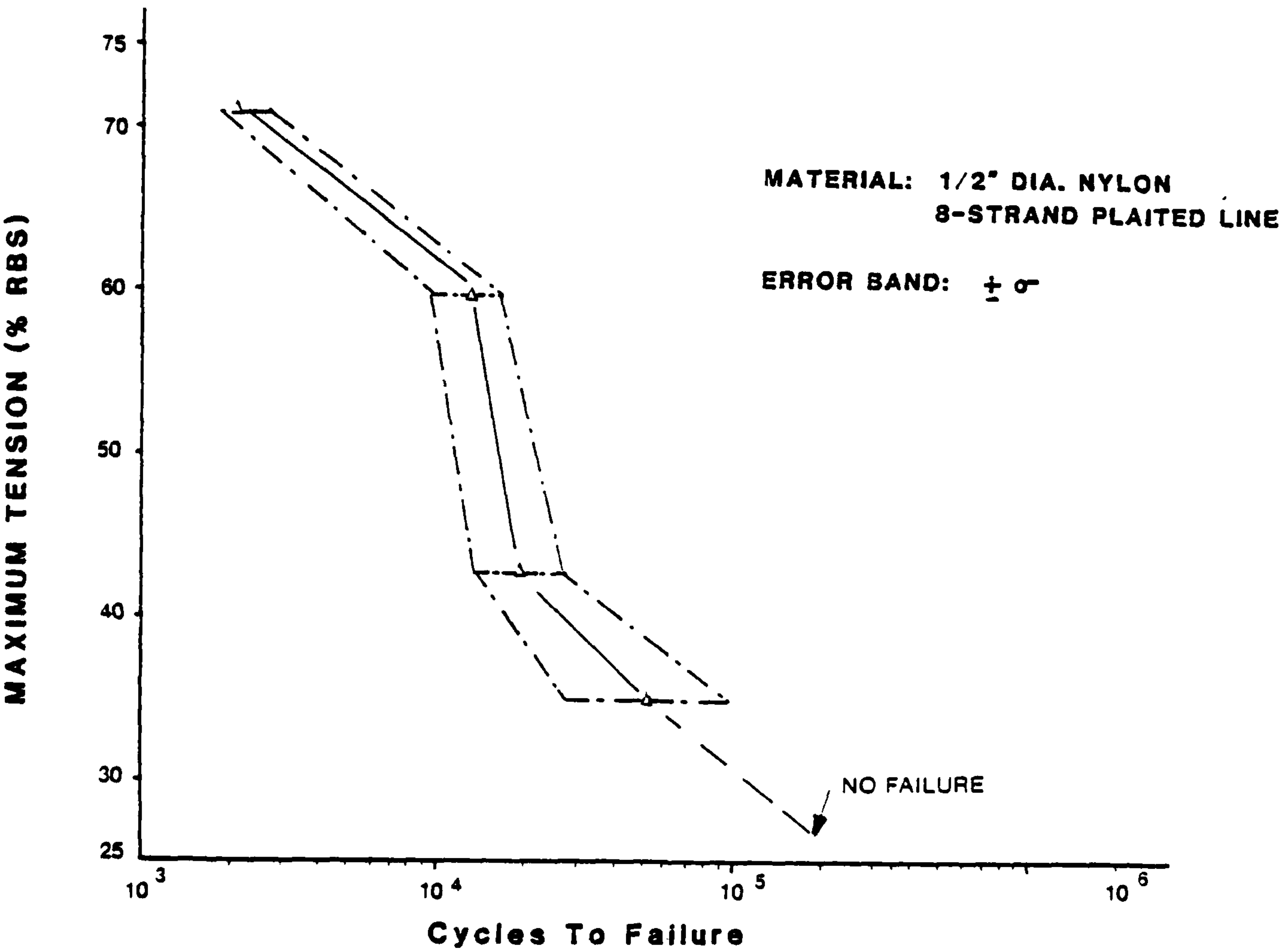


FIGURE 19

SNAP LOAD TEST RESULTS

between 27 and 35 % of rated breaking strength, the zero-minimum-load condition may not induce fatigue as observed at higher loads.

The ends of strands in the failure region are cut off and spread on glass slides for inspection under a microscope. In each yarn, many types of failure are observed. Some filaments are badly abraded and fused into bundles by the constant working of the yarns where they crossed and by the heat generated during the cyclic loading (figure 20). Figure 21 shows a typical tensile failure with the flat end and figure 22 exhibits the tail typical of fatigue failure.

5.4 Conclusions

Nylon rope exhibits the same two fundamental indications of fatigue failure as nylon filaments: a) fatigue occurs at a much lower peak load, when the minimum cyclic load is zero, than it would if some small minimum load is maintained, and b) the same fundamental failure morphology - the "tail," appears on the end of a filament that failed in fatigue regardless of whether the filament was loaded individually or as part of a stranded nylon fiber rope. Both nylon filaments and stranded fiber ropes will fail in fatigue when the maximum tension peak exceeds approximately 30% RBS.

Nylon rope cyclically loaded between 3% RBS and 62% RBS showed no statistical reduction in break strength after 200,000 cycles. In conclusion, it appears that one way to insure that nylon line will last longer in cyclic loading is to increase the minimum load above zero. This may be one reason why some nylon ropes have failed in what appears to be moderate conditions.

FIGURE 20

NYLON FILAMENT MICROPHOTOGRAPH — ABRASION DAMAGE

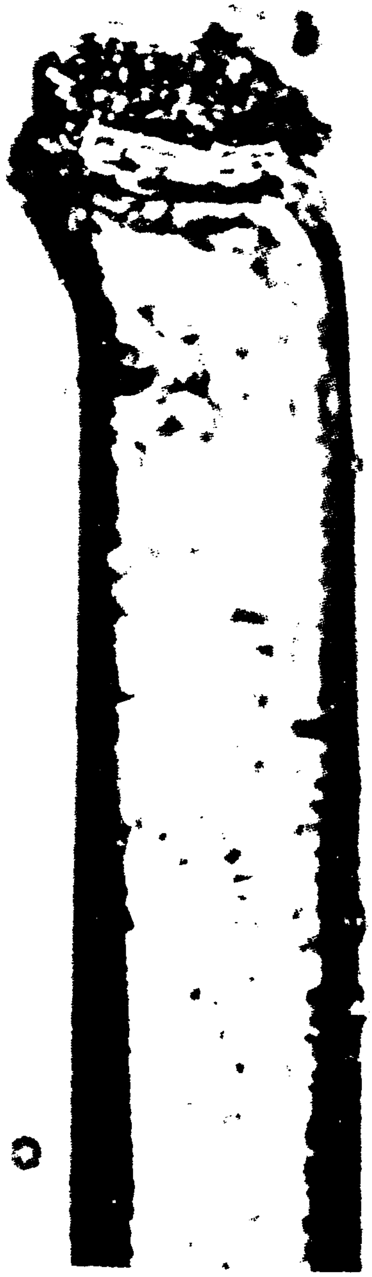


FIGURE 21

NYLON FILAMENT MICROPHOTOGRAPH — TENSILE FAILURE

FIGURE 22(a)

NYLON FILAMENT MICROPHOTOGRAPH - FATIGUE FAILURE

FIGURE 2.2(b)

NYLON FILAMENT MICROPHOTOGRAPH - FATIGUE FAILURE

6.0 ABRASION TESTING

6.1 Objectives

The objective of the abrasion testing program is to determine the abrasion properties of various synthetic mooring materials when used in a slack mooring condition where abrasion damage will occur due to contact with the ocean bottom. The program was pursued along two complementary paths: (a) laboratory testing, and (b) field testing. Laboratory tests seek to determine the relative abrasion resistance of various materials/construction combinations by subjecting them to the same abrasion conditions. The field tests provide a bridge between the actual operational environment in the ocean and the relative ranking of the materials from the laboratory test. The results of these tests are one indicator of the service life of synthetic moorings.

6.2 Laboratory Abrasion Test

6.2.1 General Approach

The abrasion resistance of synthetic materials is generally thought to be a function of a particular abrasive mechanism. Therefore, several techniques for abrasion testing have evolved, each closely aligned to the type of abrasion that each synthetic line user expects to experience. Since the tests discussed here are intended to simulate the movement of synthetic line across the ocean bottom or around a rock, a machine was fabricated which pulls a line across a carborundum stone until the line abraded through and parted. A full description of the machine is included in appendix E. Nylon and polyester line of the double-braided, 8-strand plaited, and twisted constructions and polypropylene of the 8-strand plaited and twisted constructions were abraded to failure in the machine. Several material/construction combinations were jacketed with black polyurethane to increase the abrasion protection. All samples were 1/2-inch diameter. The results are expressed in terms of number of cycles-to-failure. Since the conditions are identical for all tests, the relative abrasion resistance of the material/construction combinations are measured by the number of cycles-to-failure.

6.2.2 Results And Conclusions Of Laboratory Abrasion Tests

Results are shown in table 20 and figure 23. Plaited and braided construction shows approximately the same amount of abrasion resistance while twisted line may be somewhat less resistant. Polyester line is approximately two times more abrasion resistant than polypropylene while nylon is approximately three times more resistant than polypropylene. Polyurethane-jacketed sample tests were suspended after 13 samples because the time to failure was increasing with successive tests. The polyurethane that had abraded off may have adhered to the abrasive stone in the abrasion machine and acted as a lubricant. The stones were rotated between tests to determine if the jacketing was wearing the stones down. No change occurred. It is reasonable to assume that the first tests are the most representative of the behavior of polyurethane jacketing because the polyurethane was just beginning to have an effect on the stones. Results of the unjacketed

TABLE 20

Laboratory Abrasion Test Results

(1/2 DIAMETER)

Material	Construction	Number of Cycles to Failure		Relative Variability	Number of Samples
		Mean	Standard Deviation		
Nylon	Double Braid	13606	3331	.24	45
	8-Strand Plaited	13173	3278	.24	26
	3-Strand Twisted	12575	2835	.22	21
Polyester	Double Braid	8134	1963	.24	38
	8-Strand Plaited	8212	1763	.21	39
	3-Strand Twisted	8086	1660	.20	33
Polypropylene	8-Strand Plaited	4254	1221	.28	29
	3-Strand Twisted	6064	1621	126	12

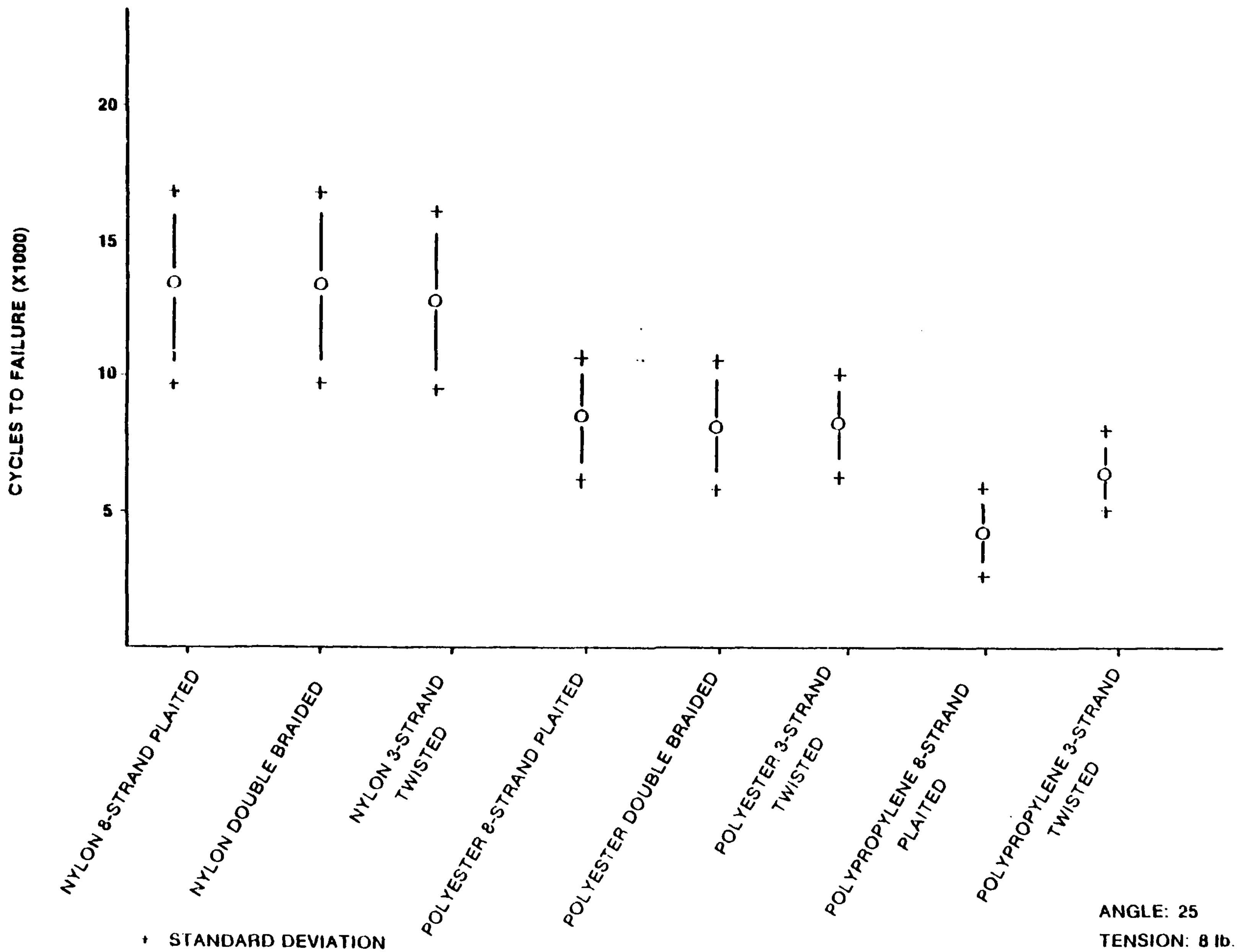


FIGURE 23

RESULTS OF LABORATORY ABRASION TESTS

polyester double-braided line indicate a range of 5,000 to 11,000 cycles-to-failure and a mode of 7,000 cycles-to-failure. The first three jacketed samples failed at 29,000, 39,000, and 41,000 cycles. Comparing that data to the mode of the unjacketed samples, it appears that polyurethane jacketing would increase the abrasion resistance of unjacketed line by five or six times.

6.3 Field Abrasion Tests

6.3.1 Mooring Configuration And Materials

Synthetic moorings were deployed on sixth class plastic buoys with a scope of 2:1 to insure that the line was in contact with the ocean bottom. Because of the large number of buoys and sinkers that would be required to test each mooring material/construction combination thoroughly, only one material/construction combination was tested extensively. The field service life of other material/construction combinations will be predicted from laboratory data and the field data of the one tested.

Polyester 2-in-1 double-braided 1/2-inch diameter line was selected for use in the field test because polyester exhibits a narrower spread in data points in the laboratory test and a lower abrasion resistance than nylon. Since data collection from this type of field test is expected to exhibit a high degree of randomness, it was thought wise to test the material that exhibits the least inherent variation. Polyester also abrades about one-and-a-half times faster than nylon and should produce data at a higher rate. Since laboratory data indicates that plaited and braided constructions abrade at about the same rate and market shortages at the time caused plaited polyester line to be in short supply, braided line was selected.

Test samples 50 feet long were deployed in 25 to 30 feet of water on a lightweight plastic buoy as shown in figure 24. A retrieval device was placed between the 200-pound cast-iron serrated sinker and the abrasion samples so that the sinker could be lifted without damaging the line sample. An explanation of how the retrieval device is employed is found in appendix F. Polyurethane thimbles were used to avoid a corrosion problem caused by the dissimilar metals of brass thimbles and galvanized chains and shackles. The vertex of the thimble is potted with polyurethane to increase the rigidity of the thimble. Polyurethane thimbles are shown in figure 25. The test sites where moorings were deployed are located in Fishers Island Sound and Gardners Bay near the R&D Center. The bottom of Fishers Island Sound is sandy silt and the bottom in Gardners Bay is gravel and cobbles.

6.3.2 Unjacketed Polyester Line Results And Conclusions

Unjacketed polyester line was deployed at Fishers Island during September 1974. The moorings were selected at random for inspection at six-month intervals. During inspection in 1976, one sample was returned to the laboratory for testing because part of it was damaged during the recovery/inspection operation. The sample was in very good condition (figure 26) and showed very little abrasion. It was tensile tested to 4,672 pounds; the break was approximately one foot from the splice which is customary. Similar new polyester double-braided line has been tested at the R&D Center

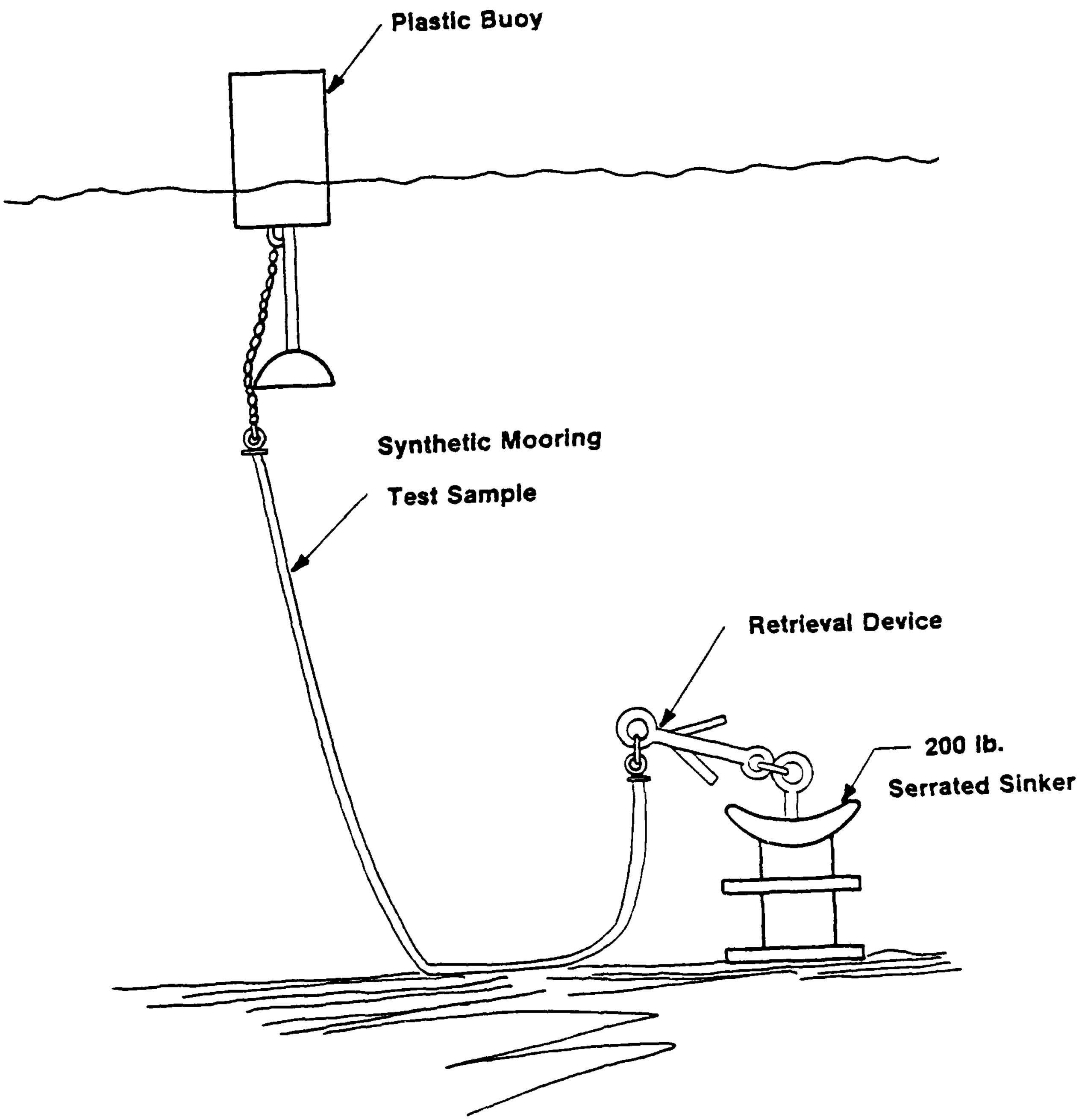


FIGURE 24

Field Abrasion Test Mooring Configuration

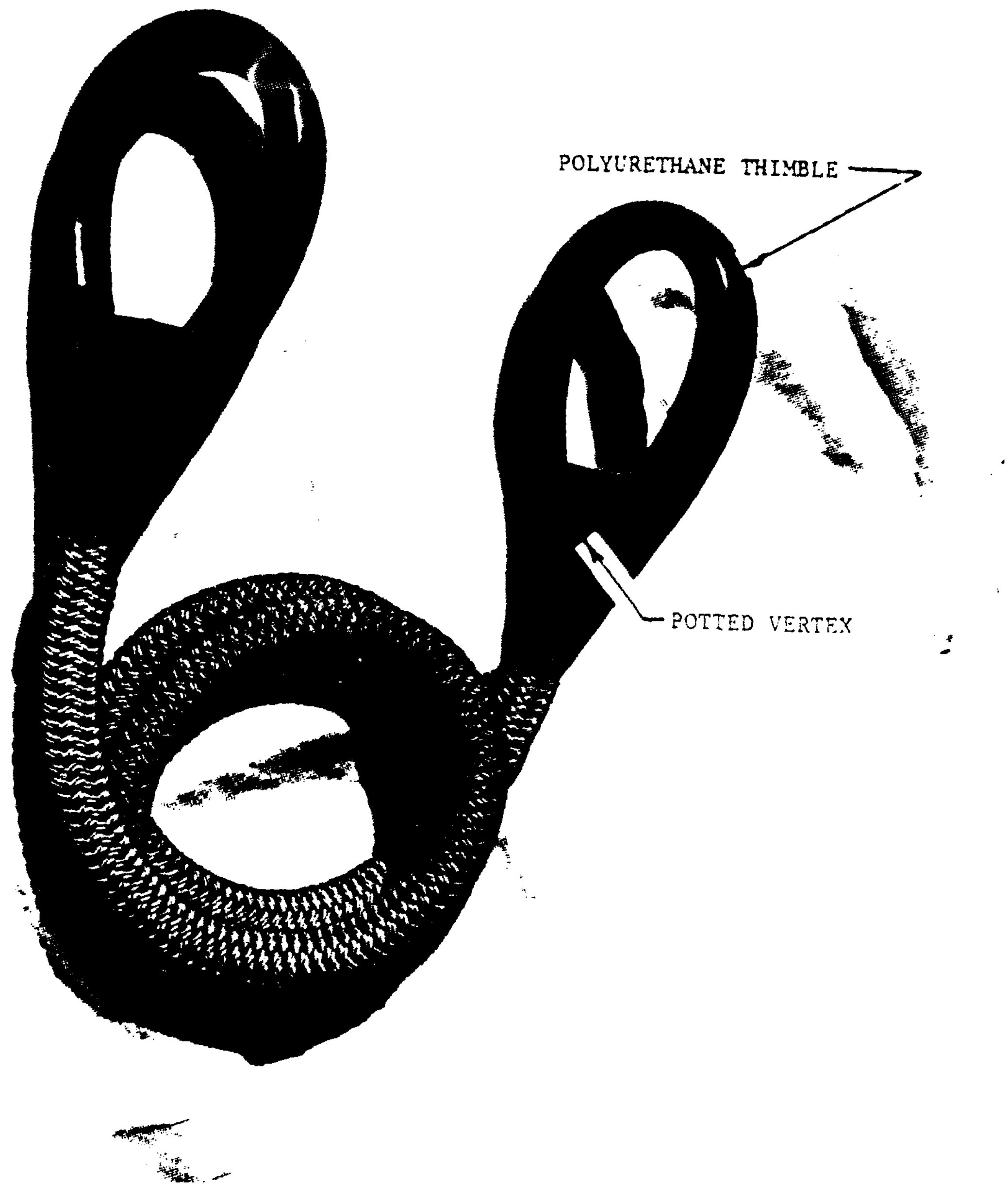


FIGURE 25

POLYURETHANE THIMBLES WITH POTTED VERTEX

FIGURE 26

POLYESTER DOUBLE BRAID LINE (UNJACKETED)
TWO YEARS OF SERVICE

(Bitting, 1975) and the tensile strength averages 6,400 pounds. The advertised rated breaking strength is 7,500.

The remainder of the samples were recovered after three years and tensile tested. The results appear in table 21. The tensile strength decreases by 32% and the elongation increases by 54%. These results are consistent with the results from the other field exposure test (table 10). Because of the lack of apparent abrasion damage, the strength reduction can be attributed to a loss of strength due to exposure to the general marine environment and analyzed with the field exposure test results (section 4.4.4). After three years of deployment, the observations of unjacketed polyester samples over sandy silt bottom are summarized as follows:

a. Minor abrasion damage was observed. Some scuffing and a few pulled yarns appeared in the chafe section.

b. Plant and animal marine fouling occurred in the top six feet of the synthetic line; the remainder of the mooring was free of growth.

c. The polyurethane thimbles were in good condition and showed no indication of abrasion or deterioration.

6.3.3 Polyurethane-Jacketed Polyester Line Results

Polyurethane-jacketed samples were deployed at the Fishers Island site (sandy silt) and the Gardners Bay site (gravel and cobbles). The samples from the sandy silt site showed no visible signs of deterioration after three years of deployment. The jacketing was intact all along its length. Evidence of some mild scuffing was apparent because the black sheen on the jacketing was somewhat dull.

Because of heavy ice during the winter of 1975-76 and suspected mechanical difficulties in the mooring, only two samples survived the first year at the gravel site. The observations are as follows:

a. The first sample was recovered with moderate growth on the entire length except the bottom ten feet. In that area, the jacketing was worn off and broken yarns (figure 27) had come through the jacketing in a number of small areas (one or two inches long) and the potting in the thimble was loose. The sample was tensile tested in the laboratory and failed at 4,200 pounds. The break occurred approximately three feet from the bottom splice at a point of abrasion damage.

b. The second sample that was recovered showed moderate marine growth all along the length except the bottom ten feet. The jacketing was completely removed from all the mooring except the middle section where the jacketing was very thin, had lost its shiny black color, and had come loose and was peeling off the line (figure 28). The bottom ten feet showed extensive

TABLE 21

Field Abrasion Test Results

Polyester Double Braid Line, 1/2" Dia.

	New[1]		Field Abrasion (3 Years)		Change
Tensile Strength	6400		4365		-32%
	473	.073	321	.073	
Elongation-at-Failure	.13		.20		+54%
	.014	.107	.045	.225	

(1) Bitting, 1975.

$\bar{X}$	
S_x	Relative Variability $\frac{S_x}{\bar{X}}$

FIGURE 27

POLYURETHANE JACKETED POLYESTER
DOUBLE BRAID LINE — CHAFE SECTION

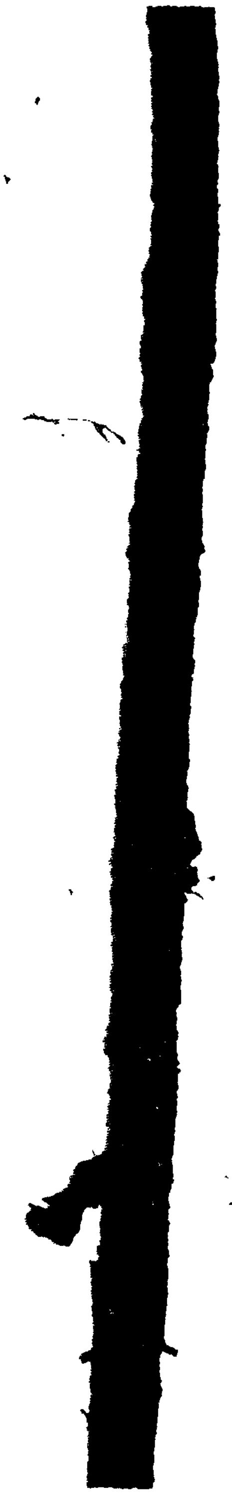


FIGURE 28

POLYURETHANE JACKETED POLYESTER DOUBLE BRAID LINE — MIDSECTION

abrasion damage in addition to the absence of jacketing (figure 29). Looking at the line as a whole, the jacketing appeared to have dissolved. The potting in the thimble was missing. The sample failed in the tensile test machine under a load of 1,869 pounds at a point about eighteen inches from the bottom eye-splice.

Of the various polyurethane-jacketed samples deployed, the latter two were the only ones that showed deterioration. The fact that the attack occurred in the area not in contact with the bottom may suggest marine fouling or perhaps quality control would be the cause. Jones (1970) indicates that some micro-organisms can cause deterioration of polyurethane. Jacketed samples inspected at the Fishers Island site showed no deterioration.

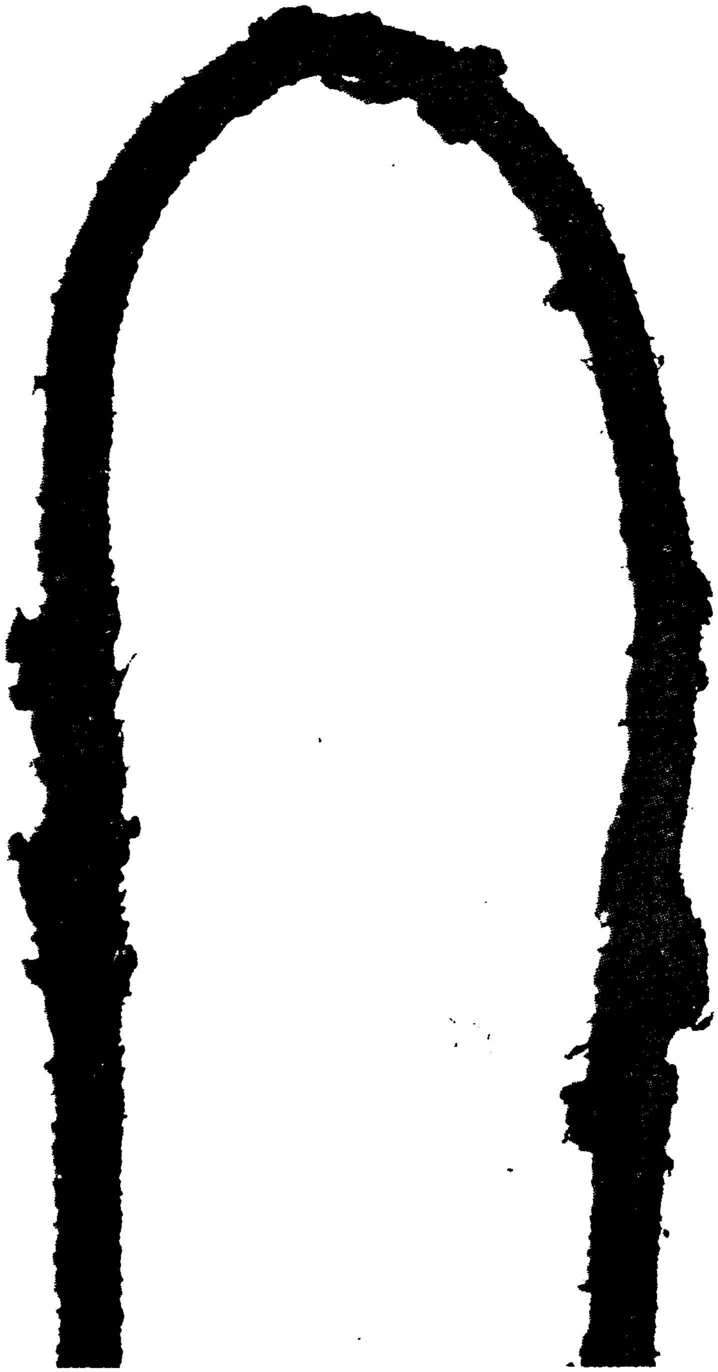


FIGURE 29

POLYURETHANE JACKETED POLYESTER
DOUBLE BRAID LINE - CHAFE SECTION

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APPENDIX A

SCREENING EXPERIMENT

To begin the quantitative investigation of synthetic mooring lines, a screening test was conducted for the purpose of determining what factors have a significant effect on the mooring material physical properties so that insignificant factors could be eliminated to ensure more efficient tests by concentrating on factors of prime interest.

A-1 Experimental Design

Factors thought to affect the physical properties of synthetic line are:

Frequency of Loading
Mean Load
Load Amplitude
Duration of Loading
Humidity
Temperature
Line Diameter
Line Material
Line Construction

Of these, frequency, mean load, load amplitude, duration, and diameter were treated as independent variables in this test program. To reduce the number of tests, the remaining variables were held constant initially and addressed as discrete variables in later tests. For example, line material and construction were treated as a discrete variable initially and tests run later to determine the material interactions with the line responses. The dependent variables tested were apparent spring constant (K_{ap}), hysteresis (H), tensile strength and strain-at-failure after the cyclic test, and the viscoelastic coefficients (K_0, K_1, τ). To efficiently determine the effect of the factors on a line characteristic, a Plackett-Burman screening design was selected. Using only twelve tests, the effects of the five factors on the line characteristics can be determined. This design, being a two-level design, does not provide an estimate of the interaction between the variables; therefore, no empirical model can be constructed from this data. It does determine the significance of each factor and an estimate of error. The "minus" and "plus" signs in the experimental design designates the lower level and upper level, respectively, of each variable. In the discussion that follows, ($-X_1$) refers to, for example, the frequency variable at the low level (0.2 Hz). A discussion of each factor follows. (Refer to table A-1 also.)

<u>Frequency (X_1)</u> - To expedite the tests, frequencies of 1.0 Hz and 0.2 Hz were used. If frequency is found not to be a significant factor (in the experimental range considered) using 1.0 Hz in subsequent tests would shorten the test program considerably.

TABLE A-1

Screening Test Factor Levels

FACTOR	LEVELS	
	Low (-)	High (+)
Frequency (f)	.20 Hz	1.0 Hz
Mean load (T_m)	15% BS	50% BS
Load amplitude (ΔT)	$\pm$5% BS	$\pm$12% BS
Duration (d)	20,000 cycles	200,000 cycles
Diameter (D)	1/2"	13/16"

BS: Break Strength

Mean Load (X_2)/Load Amplitude (X_3) - Mean load levels (X_2) of 15% and 50% of breaking strength were selected. These levels allow some boldness in choosing the load amplitude ($\pm$5% and $\pm$12% of breaking strength), in that these load amplitudes allow a high level ($+X_3$) load amplitude (i.e., $\pm$12%) that is a large percentage of the high level mean load factor (i.e., 50%). They also will not allow the sample to go slack at minimum values of low mean load level and high load amplitude. That is, the minimum tension will be 15%-12%, or 3% break strength.

Duration (X_4) - Duration (i.e., total number of cycles) is the most difficult factor to assess because buoy moorings typically undergo a very high number of cycles during service life. Because properties of viscoelastic materials are time-dependent, it is probably not possible to accelerate the tests and still achieve significant results. It is believed that a test of 200,000 cycles will be sufficient to determine the importance of the durati n factor.

Line Diameter (X_5) - Diameters of 1/2-inch and 13/16-inch were used. The spread in cross-sectional area and tensile strength should be sufficient to determine factor effects associated with the diameter. These two diameters were also selected because (a) they are within the load capacity of the cyclic/tensile test machine at the R&D Center, (b) the material was available on short notice, and (c) the R&D Center has baseline data from previous tensile tests on 1/2-inch line which will be useful in this test.

Line Construction - Nylon 8-strand plaited line was used in the screening test. Plaited line was selected initially because it has a homogeneous construction. It is not known how much the core moves relative to the cover in double-braided line and that could cause errors in the strain measurement methods. Double-braid line was tested in subsequent tests.

A-2 Test Procedure

A-2.1 Tensile Testing For Baseline Data

Load levels in the experimental design shown in table 1 are expressed as a percentage of the tensile strength of each line diameter. To determine the tensile strength independent of manufacturer's claims, nine examples of each diameter line were soaked in salt water for several days and then tensile tested while still wet. Those tensile strengths were applied to the break strength percentages in table A-1 to determine the load in pounds for setting up the cycle/tensile testing machine. (The tensile strengths are discussed in section 4.6.)

A-2.2 Cyclic Testing

Each sample was soaked in salt water for one week and then placed in the trough of the cyclic machine and cycled while underwater at the combination of variables required by the experimental design (table A-1). At intervals during the test, the hysteresis loop was recorded on an

X-Y plotter. At the end of the cyclic test, each sample was tensile tested. All cyclic and tensile tests were accomplished on the cyclic/tensile test machine at the R&D Center (appendix B).

A-3 Data Reduction Method

The hysteresis for each test was determined by measuring the area within the hysteresis loop with a planimeter. The apparent spring constant was graphically measured from the slope of the line drawn between the ends of the hysteresis loop (figure 5). Using K_{ap}, K_0, H, and ω as knowns, equations 1 and 4 were solved simultaneously to determine K_1 and τ .

The effect of each loading factor on a response (i.e., material property) is calculated by using the Plackett-Burman data reduction technique. The factors are then ranked according to the absolute value of the calculated factor effects. Any factor having an effect greater than the minimum significant effect is statistically significant and should, therefore, be investigated in more detail. If interactions do exist between factors, the interactions are mathematically separated into many parts which act to inflate the experimental error and increase the minimum significance factor effect. Thus, when a factor effect is found to be significant, that factor stands out over a pool of background noise containing both experimental error and interactions. The confidence limit assigned to the minimum factor effect must be set rather low (i.e., 90%) to increase the likelihood of detecting a significant factor. Where a small number of significant factors are found, the data is pooled to permit further investigation.

A-4 Results

Table A-2 is a matrix displaying the independent variables versus the responses (material properties). The box of each significant factor effect shows a diagonal as well as the factor effect associated with that factor and response. The column at the right shows the minimum significant factor effect as calculated from the Plackett-Burman Technique. This table is provided as a ready summary of the results; an interpretation of the results follows.

A-4.1 Apparent Spring Constant, K_{ap}

The results (table A-2) show that the apparent spring constant (K_{ap}) is highly dependent on the mean load. This is not observed directly from equation 1; however, it will be seen later that this is probably a reflection of the nonlinearity of nylon line. Frequency, as predicted by equation 1, is also shown to have an effect on K_{ap} (secondary to the mean load). Even though the factor effect of frequency is less than the minimum significant effect, that variable should be a factor in future tests because (a) if fewer variables had been used in this screening test, the errors associated with the frequency factor may have been more accurately determined and it may have fallen above the minimum significant factor effect; and (b) the theory and data indicate that it should be an important factor.

TABLE A-2

Screening Test - Summary of Results

	Frequency f	Mean Load T_m	Load Amplitude ΔT	Duration d	Diameter D	Minimum Significant Factor Effect
Apparent Spring Constant K_{ap}	6.1	14.3	3.1	5.3	3.7	7.72
Dissipation Spring Constant K_1	5.2	8.3	3.5	5.0	.6	8.0
Quasi-Static Spring Constant K_o	.5	6.5	1.1	.2	1.6	1.5
Characteristic Relaxation Time τ	5.3	2.3	5.7	4.5	4.2	10.79
Hysteresis H	.7	6.6	6.1	.5	4.5	3.12
Tensile Strength T_f	.5	.1	.4	1.0	9.4	1.4
Elongation at Failure ϵ	6.9	8.1	0.0	6.6	9.4	7.0

Duration, or the total number of cycles, appears as a weak factor. Therefore, that variable was held constant in similar tests in the future.

The results indicate that the load amplitude does not have a significant effect on the apparent spring constant, K_{ap}. While this is in keeping with the theory, it is contrary to earlier work by Paquette and Henderson (1965). Since the test frequencies used here and by Paquette and Henderson (1965) are very different, it is difficult to identify the cause of the discrepancy.

The most significant result regarding K_{ap} is its magnitude with respect to K_o, the quasi-static spring constant. For all frequencies and load amplitudes tested, the apparent spring constant, K_{ap} is three to four times greater than K_o. That means that if the mooring is taut and excited at a period of one to five seconds, the forces would be three to four times higher than those predicted if K_o is used to character- ize the elasticity as is often the case because of its availability from manufacturers' data.

All values of K_{ap} approximate equation 2; that is, K_{ap} is approximately equal to K_1 plus K_o. That means there is very little energy dissipated between 0.2 Hz and 1.0 Hz. This factor is illustrated in figure A-1. The dash line marks the $\omega\tau$ value of less than 10% of the theoretical maximum energy that could be absorbed by the synthetic line. The dash line also intersects the K_{ap} curve in a region where the curve is becoming flat which indicates that an increase in frequency would not result in much increase in K_{ap} or in internal damping. It should be noted that the $\omega\tau$ values of all tests conducted in these tests are greater (i.e., lay to the right of the dashed line) than the one illustrated in figure A-1.

A-4.2 Quasi-Static Spring Constant, K_o

The quasi-static spring constant, K_o, is the slope of the load-strain curve recorded during a slow uni-directional loading such as a tensile test. It is a strong function of mean load (table A-2). In figure A-2, K_o is plotted versus the mean tension. It is seen that K_o increases significantly with mean tension.

The factor effects in table A-2 verify that K_o is a weak function of diameter in these tests and a strong function of mean load.

Figure A-3 shows the load-elongation curves for 13/16- and 1/2-inch diameter line as determined from the experimental data. It is compared with a load-elongation curve published by the rope manufacturer. While the slopes (i.e., K_o) predicted by the experimental and manufacturer's data are similar, the actual elongation at any mean load is different between the three sets of data.

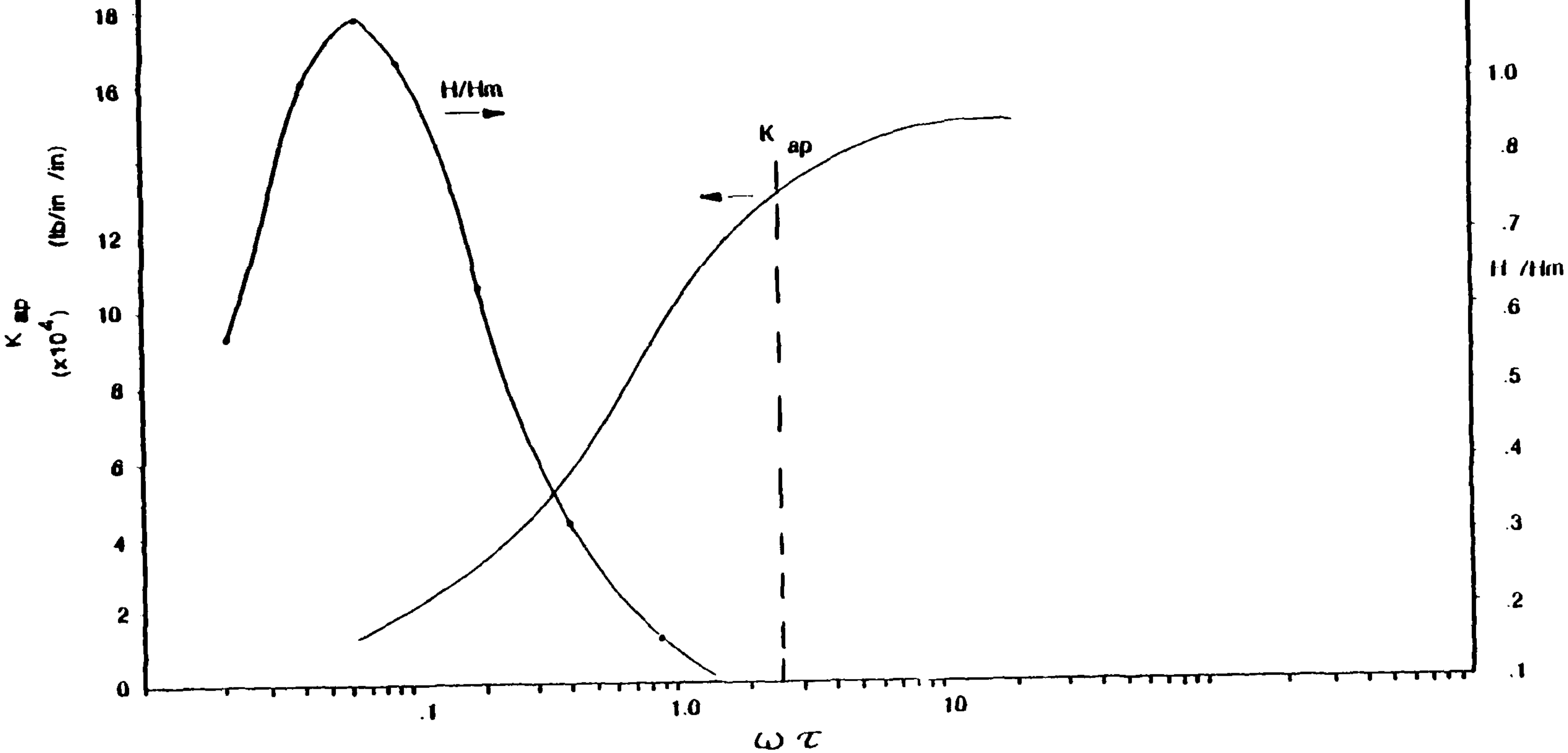

FIGURE A-1
H and K_{ap} versus $\omega\tau$

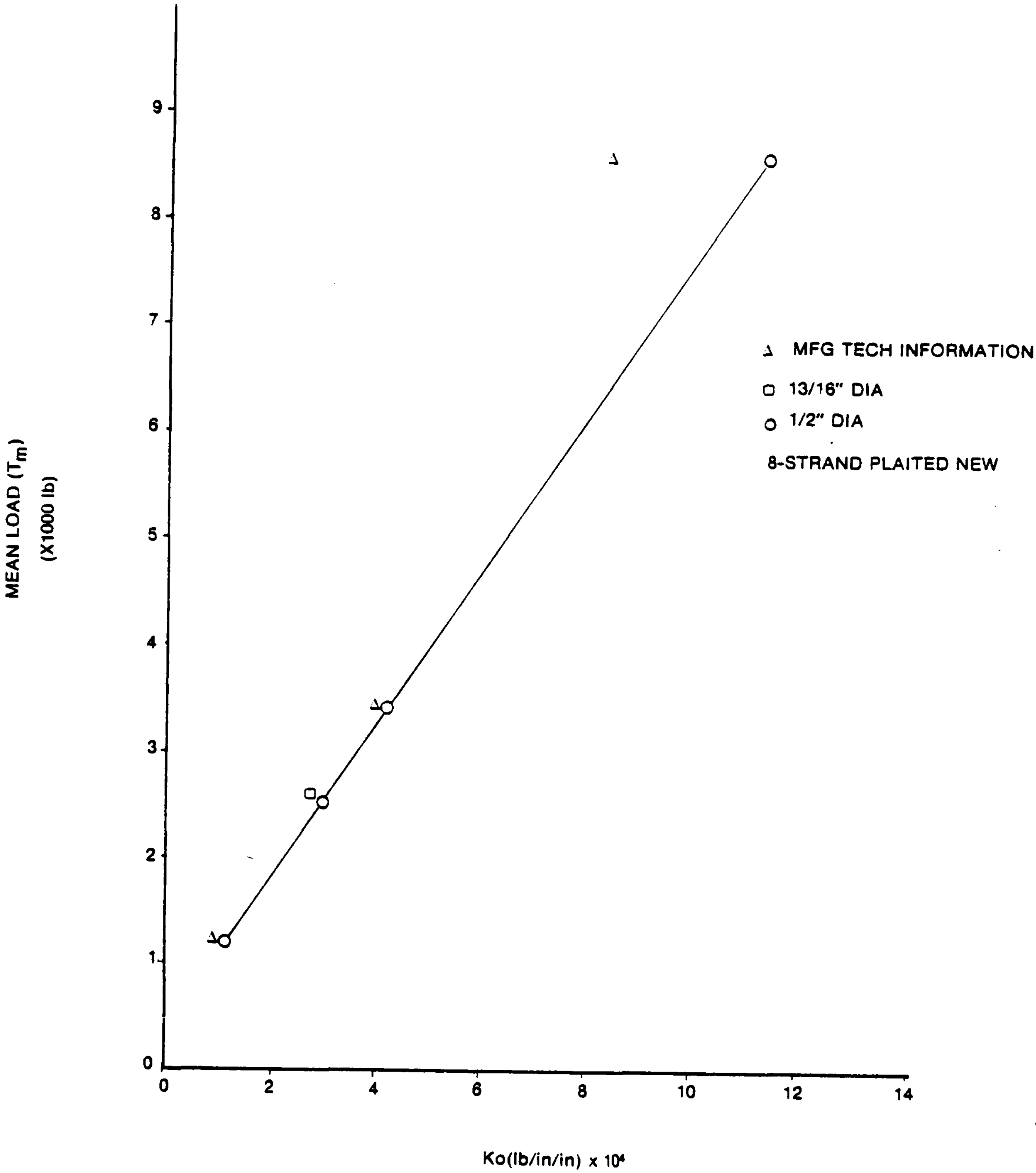

FIGURE A-2

Tm Versus Ko

A-4.3 Dissipation Spring Constant, K_1

The dissipation spring constant, K_1, associated with the damping mechanism is found to be predominantly a function of mean load. This is plausible because K_0 is a function of mean load (because of the inherent nonlinearity of nylon) and K_1 is calculated using K_0. The frequency and duration factors fall below the minimum significant factor effect; however, the weak appearance of these factors may be caused by the weak frequency and duration dependency of K_{ap} which is also used to calculate K_1. Intuitively, K_1 should not be frequency dependent because springs react the same regardless of the rate of loading. K_1 was found to be two to three times greater than K_0.

A-4.4 Characteristic Relaxation Time, τ

The low factor effect values in table A-2 suggest that none of the factors has a significant effect on τ. This suggests that τ is truly a property of the material. The high minimum significant factor effect may also indicate a high degree of interaction among the factors tested as discussed in section A-1. Further work (section 4.4.7) will show that, while the mean value of τ is relatively constant for a material/construction combination, it is greatly affected by mean load, load amplitude and frequency. The high minimum significant factor effect in these tests indicates that there are many interactions among the test factors and not that the test factors have no significant effect on τ. The mean value of τ was calculated to be 3.05 seconds in these tests.

A-4.5 Hysteresis, H

Hysteresis (H), the amount of energy dissipated during one cycle, was found to be sensitive to mean load, load amplitude, and line diameter (table A-2). Theory (equation 4) predicts the load amplitude dependency of H. The presence of the mean load and diameter as significant factors is probably due to the inherent nonlinearity of nylon. While theory indicates that H is a function of frequency, experimental results obtained in this work and by Paquette & Henderson (1965) show no frequency dependency in the frequency range of test.

If equation 4 is maximized, the maximum amount of energy (H_m) that would be dissipated by the line in one cycle could be calculated. The ratio of H to H_m is the percentage of maximum energy that is dissipated. For all cases tested in this experiment (represented by dashed line), H/H_m is less than 0.1 as illustrated in figure A-1.

A-4.6 Tensile Strength And Strain-At-Failure

Tensile tests were conducted on new wet line and on line that has been cycled according to the test plan. The Plackett-Burman Data Reduction Technique shows that (table A-2) tensile strength is sensitive to only line diameter, and it is not sensitive to any other dynamic loading factors tested. This is a confirmation of the simple fact that 13/16" diameter line is stronger than ½" diameter line. The most interesting results, however, are found in the comparison of data for ½" diameter line. The tensile strength of new, wet, uncycled ½" diameter line (from

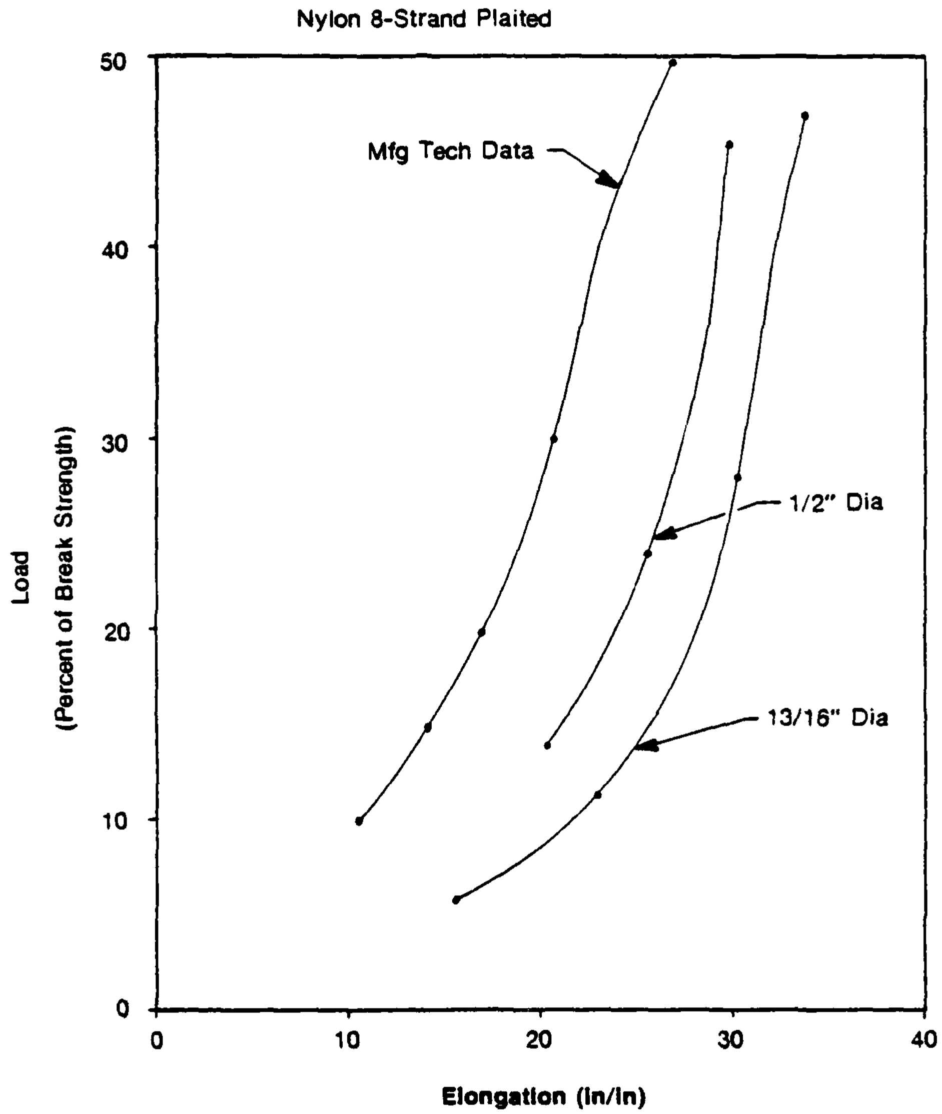

FIGURE A-3

Load - Elongation Curves (Screening Test)

Bitting 1975) is reduced by approximately 12% when it is soaked in water (table A-3). This fact is well known (Paul 1970). When wet line is cyclically loaded, however, the strength increases to the tensile strength of new, dry, uncycled line. (table A-3) An initial observation might conclude that the effect of wet/dry is being observed in the cyclic test rather than the uncycled/cycled effect. The fact that 13/16" diameter line does not exhibit the same characteristic has not been explained. The lack of effect of cyclic loading in this test (where the minimum load is not zero) is in stark contrast to the results of the snap load tests (minimum load is zero in every cycle) in which lines failed after relatively few cycles. The snap load tests are discussed in section 5.0.

The strain-at-failure recorded during the tensile test was found to be sensitive to the mean load and diameter (table A-2). The strain-at-failure data for 13/16-inch diameter line shows no significant variation among high and low mean load levels and the uncycled wet strain-at-failure (table A-4). Half-inch diameter line at the low mean load level is not significantly different from the uncycled wet strain-at-failure. The high mean load level shows a significant variation from the low mean load level and the uncycled wet data. This trend is sufficiently strong to cause the mean load to be identified as a significant factor by the Plackett-Burman screening design.

Comparing the dry and wet strain-at-failure for 1/2-inch diameter line (table A-4) shows a significant increase in strain for the wet samples (no cycling). It is interesting to note that the strain-at-failure of the wet sample cycled at high mean load is similar to dry uncycled line. A similar trend is also observed in the tensile strength data (discussed above).

A-5 Conclusions Of The Screening Experiment

1. The Apparent Spring Constant, K_{ap}, is three to four times greater than the Quasi-Static Spring Constant, K_o. Therefore, mooring forces may be greater than those predicted by a dynamic computer program using K_o to characterize the line. The Quasi-Static Spring Constant is typical of the load elongation data published by line manufacturers.

2. Of all the loading factors used in these tests, the mean load has the predominant effect on the properties of nylon 3-strand plaited line. That is indicative of the inherent non-linearity of nylon.

3. The quasi-static spring constant, K_o, is predominantly a function of mean load.

4. The characteristic time constant, τ, is a fundamental property of the material.

5. Hysteresis is not a function of the frequency of excitation in the frequency range of .2 Hz to 1.0 Hz.

6. Internal damping was generally less than 10% of the theoretical maximum.

TABLE A-3

Tensile Strength Variation As A Result Of The Screening Test (Tension/Tension Cyclic Loading)

Diameter	Condition	Tensile Strength Mean (lbs)	Standard Deviation (lbs)	F-Static	F-Static (Critical)
1/2"	Dry[2] (No Cycle)	7850	460	26.87	$F^{(1)}(05,1,20) = 4.35$
	Wet (Before Cycle)	6920	320		
	Wet[2] (After Cycle)	7640	180	29.24	$F(05,1,13) = 4.67$
13/16"	Wet (Before Cycle)	17530	900	.61	$F(05,1,13) = 4.67$
	Wet (After Cycle)	17030	1630		

Nylon 8-Strand Plaited Line
(1) F statistic from Miller and Freund, 1977, pg 490
(2) $df_1 = 1$; $dF_2 = 17$; $F = 1.30$; $F(05,1,17) = 3.45$

TABLE A-4

Strain-At-Failure Variation As A Result Of Screening Test (Tension/Tension Cyclic Loading)

Dia.	Mean Elongation-at-Failure (∈) (Percent)				
1/2"	Mean Load Factor Level (Standard Deviation)		F-Statistic		
	Low	High	Compare Low with Original (1)	Compare High with Original (1)	Compare Low with High
	38.30 (2.00)	24.70 (1.42)	F = .83 F(05,1,10) = 4.96	F = 18.13 F(05,1,10) = 4.96	F = 89.79 F(05,1,4) = 7.71
	(1) Original (Wet, no Cycle) = 42% (6.80) Original (Dry, no Cycle) = 28% (2.34)			F = 42.75 F(.05,1,21) = 4.32	
13/16"	41.9 (9.82)	39.50 (9.12)	F = .33 F(05,1,10) = 4.96	F = .003 F(05,1,10) = 4.96	F = .10 F(05,1,14) = 7.71
	(1) Original (Wet, no Cycle) = 39.7% (4.57)				

Nylon 8-Strand Plaited Line
( ) = Standard Deviation

7. Tensile strength is generally not significantly affected by cyclic loading conditions in which the minimum load is not zero. However, an increase in tensile strength was observed for 1/2-inch diameter line. The observed difference in tensile strength may be due to the wet/dry variation rather than the cycled/uncycled variation.

8. Strain-at-failure is generally not a function of loading conditions except for 1/2-inch diameter samples cyclically tested to 50% of rate breaking strength. The strain-at-failure of wet, cycled line at the high mean load level is: (a) significantly different from that at the low load level (wet, cycled); and (b) the same as the strain-at-failure of new, dry, uncycled ½" diameter line.

9. The duration factor (i.e., total number of cycles) is a weak factor and should be assigned a suitable constant in future tests, depending on the nature of the test.

10. The effect of diameter on the properties of the material tested is a weak but persistent factor. It should be investigated more fully in future tests.

APPENDIX B

CYCLIC/TENSILE TESTING MACHINE

A combination cyclic and tensile test machine has been designed and fabricated at the R&D Center. It consists of a 12-foot stroke hydraulic cylinder at one end and a 10-inch stroke cyclic cylinder at the other end. When used as a cyclic machine, a test sample is mounted between the two cyclinders. After the large cylinder positions the sample, it remains stationary and the 10-inch cyclic actuator applies a cyclic load or displacement to the sample. During a tensile test, the cyclic actuator is removed and the end of the line is attached to a dead head. The 12-foot stroke cylinder is then used to pull the sample to failure. During the test, the strain in the sample is measured using the dual-sheeve extensometer. The strain and load are recorded on an x-y plotter.

A description of the individual components follows:

a. Test Frame. A composite structure fabricated from twin 46-foot long I-beams. Maximum allowable working load is 33,000 pounds. Useable test bed length is approximately 34 feet.

b. Tensile Hydraulic Cylinder

Stroke: 155 inches
Crosshead speed: 4-56 inches per minute

c. Cyclic Actuator

Maximum load: 11,000 pounds
Frequency: 0.01 to 1100 Hz
Input waveform: Sine, saw-tooth, square, ramp

d. Hydraulic Programmer. The hydraulic programmer is a close loop servo-system. A mean load is set into the programmer along with the load amplitude, frequency, and type of waveform. Once the programmer is started, a cycle counter records the number of cycles completed and can be set to stop the program at a predetermined cycle count. An error detector can be activated to indicate when the cyclic actuator is not keeping up with the input program. Either the load in the sample or the actuator displacement can be used as a controlling variable in the program.

e. Dual-Sheeve Extensometer. This device measures the elongation of a line sample over a gauge length in the middle of the sample. The elongation is mechanically transmitted by fine cables from the sample to the extensometer as the sample elongates. The extensometer produces a DC voltage proportional to the difference of displacement of the two ends of the gauge length and represents the elongation. The method permits accurate measurement of strain up to failure of the line without risk to the sensor.

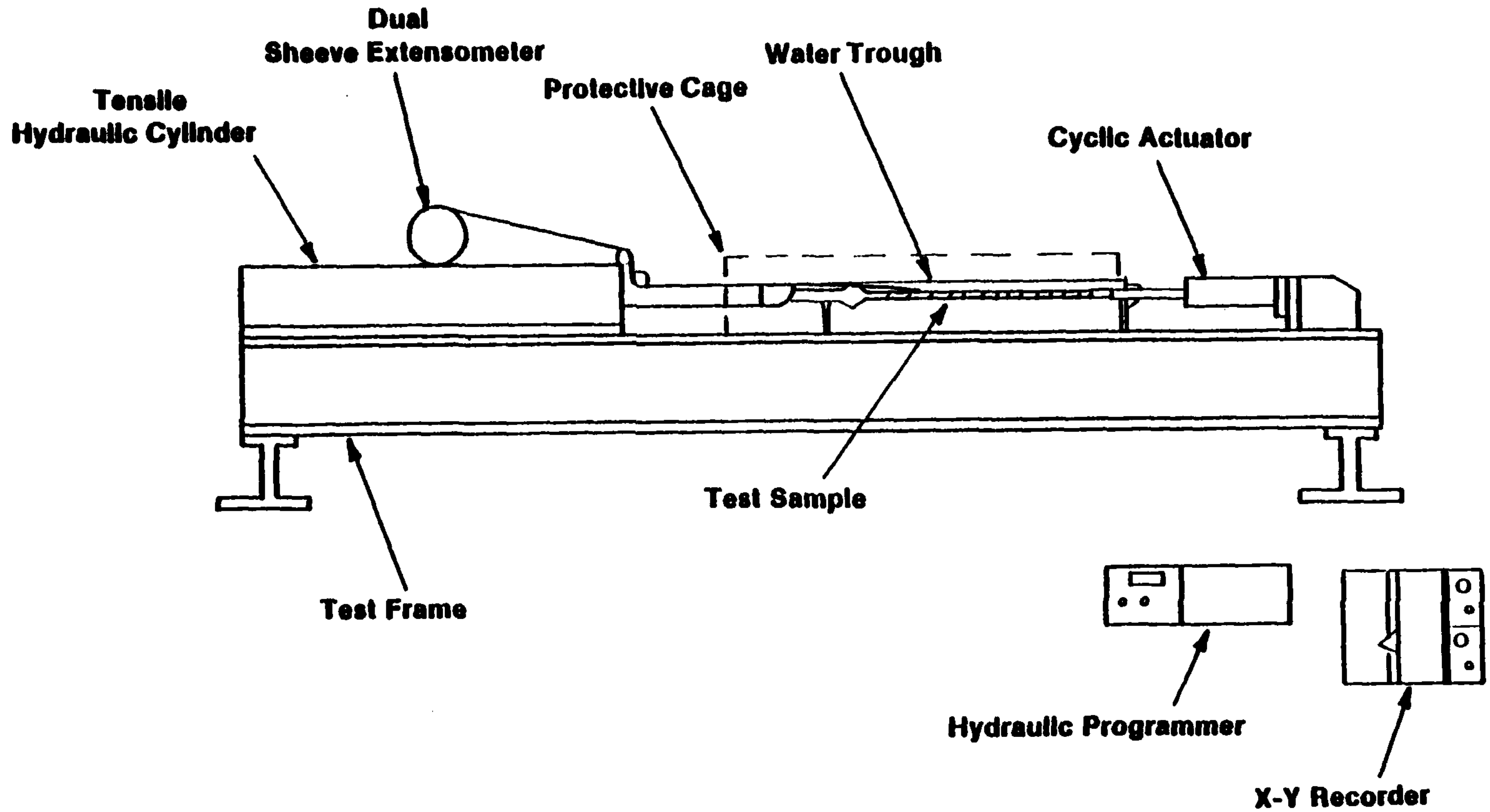

FIGURE B-1(a)

Cyclic/Tensile Testing Machine Schematic

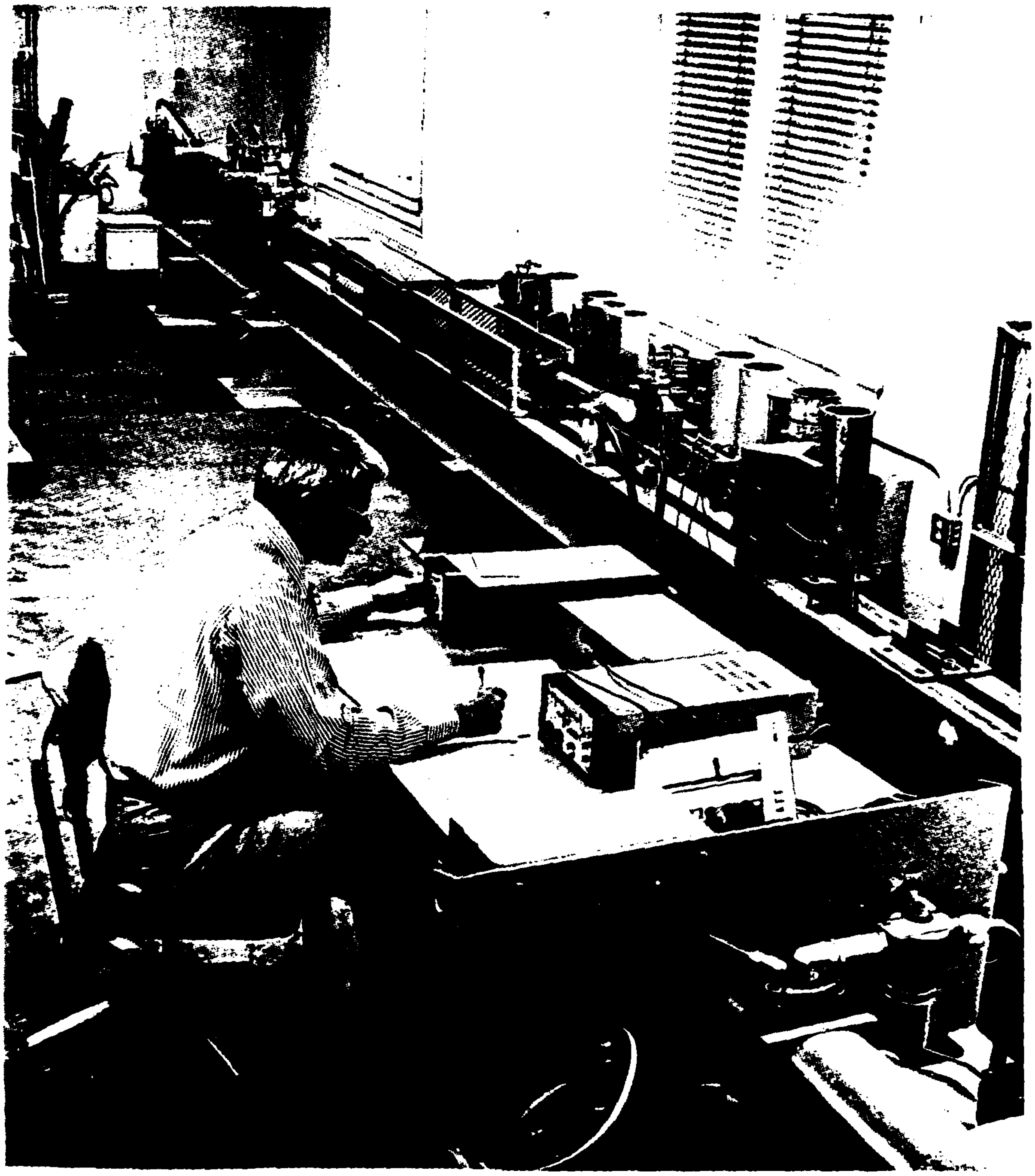

FIGURE B-1(b)

APPENDIX C

CONVERTING "CODED" BOX-BEHNKEN POLYNOMIAL REGRESSION EQUATIONS TO ENGINEERING UNITS

It is necessary to convert equation (5) from the "coded" equation into engineering units so that the material property can be calculated at any level between the limits of experimental range. Observing table 1, it is noted that the (-) factor level and (+) factor level are equi-distant from the middle factor level (0). The regression equation (equation 5) works for values of X between -1 and +1. In order to use engineering units in the equation, then, the engineering units must be converted to some value of X between -1 and +1. This is simply done with the equation:

$$X = \frac{\text{factor level} - \frac{(Hi+Lo)}{2}}{\frac{Hi-Lo}{2}}$$

Where Hi = Factor value at the high level (+1)
Lo = Factor value at the low level (-1)
Factor Level = Factor level X at which the material property is to be found.

For example, let the factor levels in the experiment be given by:

	FACTOR LEVELS		
	-1	0	+1
Mean load (T_m)	200	400	600

If it is desired to solve equation 5 for a mean load of 300 pounds, X is determined as follows:

$$X = \frac{\text{factor level} - \frac{(Hi+Lo)}{2}}{\frac{Hi-Lo}{2}}$$

Hi = 600 pounds
Lo = 200 pounds
desired factor level = 300 pounds

$$X = \frac{300 - \frac{(600+200)}{2}}{\frac{600-200}{2}}$$

$$= \frac{300-400}{200}$$

$$= -\frac{1}{2}$$

In other words, 300 pounds is halfway between the middle value (400 pounds) and the low value (200 pounds), or $X = -1/2$. The value of $X = -1/2$ is entered into equation 5. If the desired factor level had been 500 pounds, $X = +1/2$ would be entered into equation 5.

APPENDIX D
THE EFFECT OF TEST CONDITIONS ON THE QUASI-STATIC SPRING CONSTANT, K_0

The quasi-static spring constant is affected by rate of loading, the maximum loading, and time between removal of the maximum loading and loading again to record the load-elongation curve (i.e., recovery time). Tests were conducted to investigate the magnitude and variation of K_0 with the load rate and time between dynamic tests and measurement of K_0. A statistical test was applied to the data to confirm that K_0 is a function of those conditions; the data is shown in table D-1.

TABLE D-1

Quasi-Static Spring Constant, Ko, Variation With Strain Rate And Time Since Dynamic Loading

	STRAIN RATE $\left(\frac{\frac{in}{in}}{min}\right)$	$K_o \times 10^4$ $\left(\frac{lbs}{\frac{in}{in}}\right)$
24 Hours After Dynamic Test	.071	4.22
	.23	6.33
Immediately After Dynamic Test	.23	7.71

APPENDIX E

ABRASION TESTING MACHINE

Description: The abrasion testing machine is designed to move three line samples across a synthetic stone while immersed in water.

The angle of wrap of the sample around the stone, stroke, and line tension can be varied. The frequency of oscillation is fixed at 44 cycles per minute. A schematic of the abrasion machine appears in figure E-1. The driving line is attached to the crank on a 44-rpm motor and passes through several blocks down into the water where it is tied to the test sample line. The sample passes horizontally across the bottom, under the carborundum stone (a), through the variable block (b), through the tensioning block (c), and terminates in a turnbuckle (d). The position of the variable block (b) determines the angle of wrap of the sample around the stone. Line tension is varied by changing the moment arm caused by the counterweight on the tensioning block (c). During operation, the block (c) oscillates from the vertical position to the left. The turnbuckle (d) provides for adjustment of the block (c) as the line elongates during the test.

Operation: At the beginning of the test, the time on the abrasion machine clock is noted. When a line fails, the tension block (c) assembly falls forward and opens a switch that turns off the motor and clock. The time is noted and the test restarted. The sequence is followed until all the samples have failed. Knowing that the motor turns at 44 cycles per minute, a simple calculation gives the total cycles to failure for each sample.

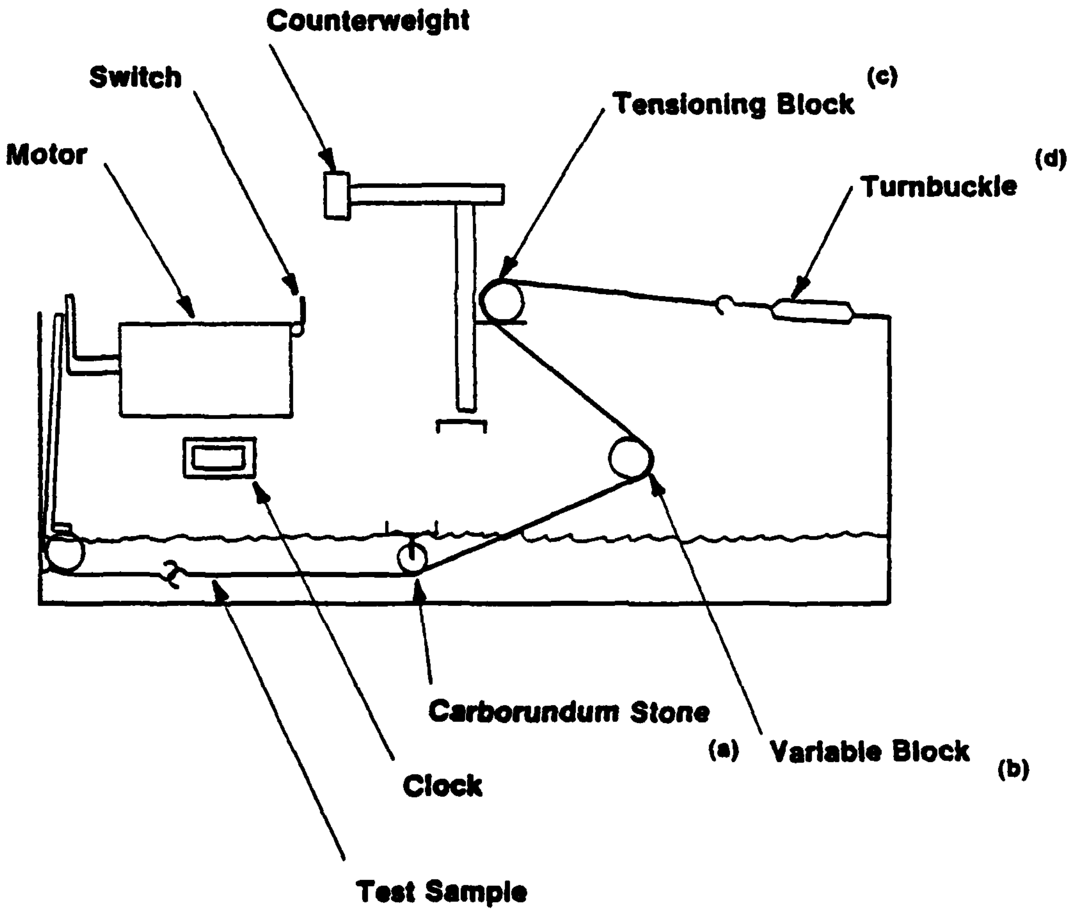

FIGURE E-1

Abrasion Testing Machine Schematic

APPENDIX F

RETRIEVAL DEVICE

The R&D Center has developed a simple retrieval device for recovering buoy moorings composed of synthetic mooring materials. The device, used by the R&D Center in all synthetic moorings since July 1973, was developed in support of the lightweight mooring materials program at the R&D Center. The retrieval device is placed between the mooring line and sinker and is used in the following way (figure F-1):

(1) The mooring line is held at short stay and the ring-like retriever is placed over or around the mooring line.

(2) The retriever is lowered to the bottom of the mooring where it is engaged by one of the three arms of the lifter.

(3) The sinker is then lifted to the surface using a winch or capstan.

The retrieval device can be used in situations where (1) the vessel does not have special equipment to recover synthetic materials, (2) it is advantageous not to subject the mooring line to the stress of recovery, and (3) the mooring cannot sustain the weight of a sinker (as in the case of the rubber band mooring).

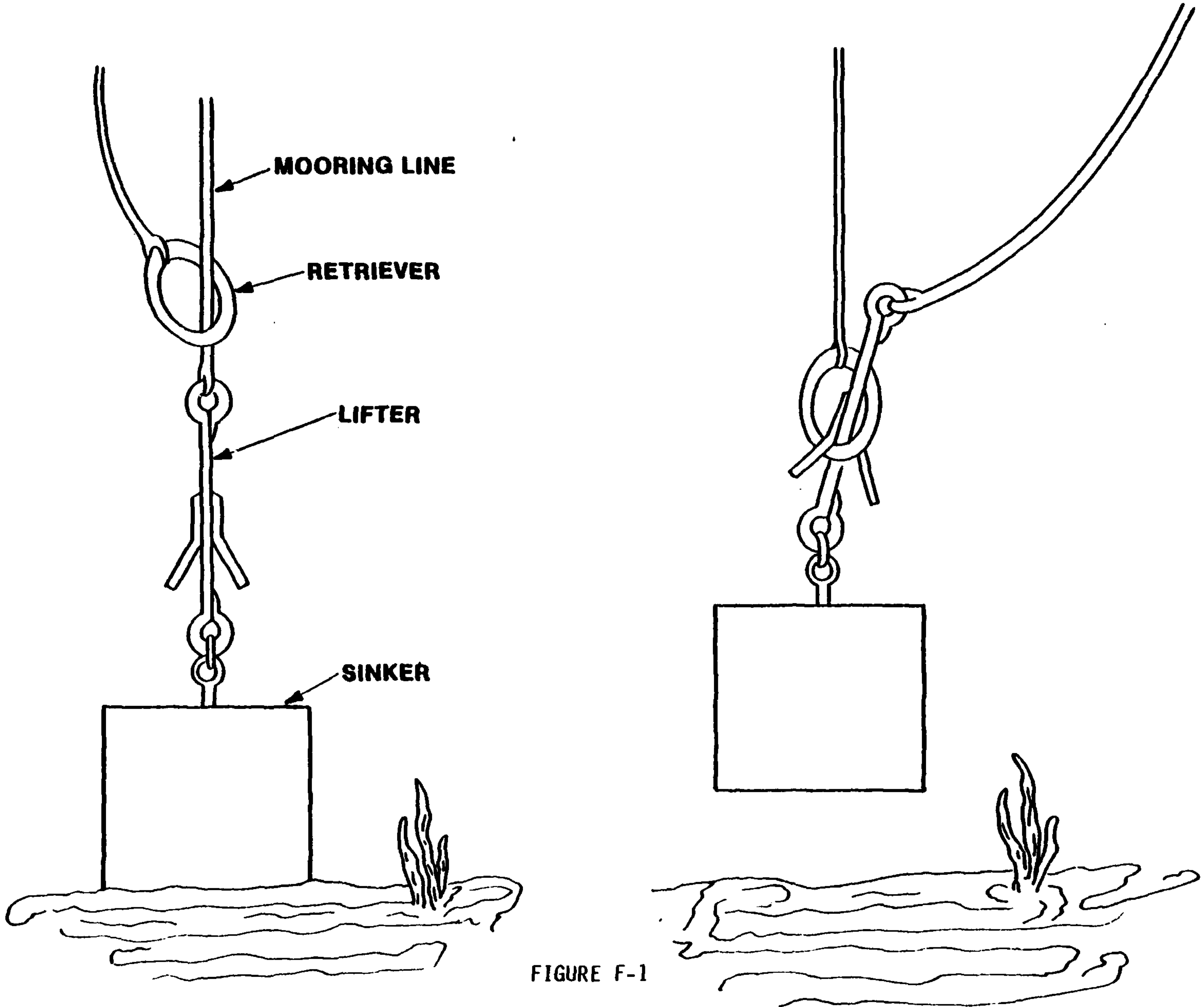

FIGURE F-1

Mooring Retrieval Device Schematic

APPENDIX G

BUOY AND HARDWARE PERFORMANCE OBSERVATIONS

Figure G-1 shows the mooring configuration used in the field tests discussed in section 4.4. The mooring composition was: lightweight plastic buoy, 3-1/2 feet of 1/2-inch galvanized chain, 20 feet of synthetic line, 40 feet of 1/2-inch galvanized chain, and two 200-pound cast iron serrated sinkers. The chain at the bottom of the mooring was used so that (1) the samples could be replaced without lifting the sinker, and (2) the samples would not touch the bottom.

The following observations were made from these moorings.

a. Polyurethane Thimbles. The field samples were deployed with brass NEWCO thimbles on the ends. When a mooring line tension recorder was placed in the mooring, the galvanized shackle between the brass thimble and the Lexan insert in the tensiometer failed by corrosion in approximately 100 days. The galvanic cell set up by the dissimilar metals of the thimble and shackle was compounded by the corrosion "area affect." That is, the galvanized shackle alone supplies current to the brass thimble because the shackle is isolated from other metal by the Lexan insert in the tensiometer. In cases where the tensiometer was not used, the 3-1/2 foot tail chain on the buoy supplied current to the brass thimble also and helped relieve the "area affect" and protect the shackle.

Polyurethane thimbles (figure 25) have been used to avoid the corrosion problem. In addition to the inert and tough characteristics of polyurethane thimbles, they cost approximately one-third less than brass thimbles.

b. Rolyan Aids-To-Navigation Buoys. The R&D Center has approximately 100 Rolyan lightweight plastic aids-to-navigation buoys. Forty buoys were deployed originally and, except for two, most performed well for the first 3 to 4 years. One sank in the first week. It was recovered and found to be only half filled with foam. The second buoy was relieved when it was noticed riding low in the water. It was not completely filled with foam also.

The most damage observed on the buoy was crushing of the top (figure G-2). During visits to the test site in the first 3 to 4 years, a few buoys were observed with damaged tops. At the time of recovery, it appeared that a large number had been damaged. It is not known what caused the damage; other than collisions with boats, it has been suggested that extraordinarily thick ice floes may have caused damage during the winter of 1976 and 1977.

Using the mooring configuration in figure G-1 (2-to-1 scope), maximum mooring line forces of approximately 150 to 175 pounds have been recorded. The test site is exposed to heavy weather from all directions except north and is in the flume of the Connecticut River.

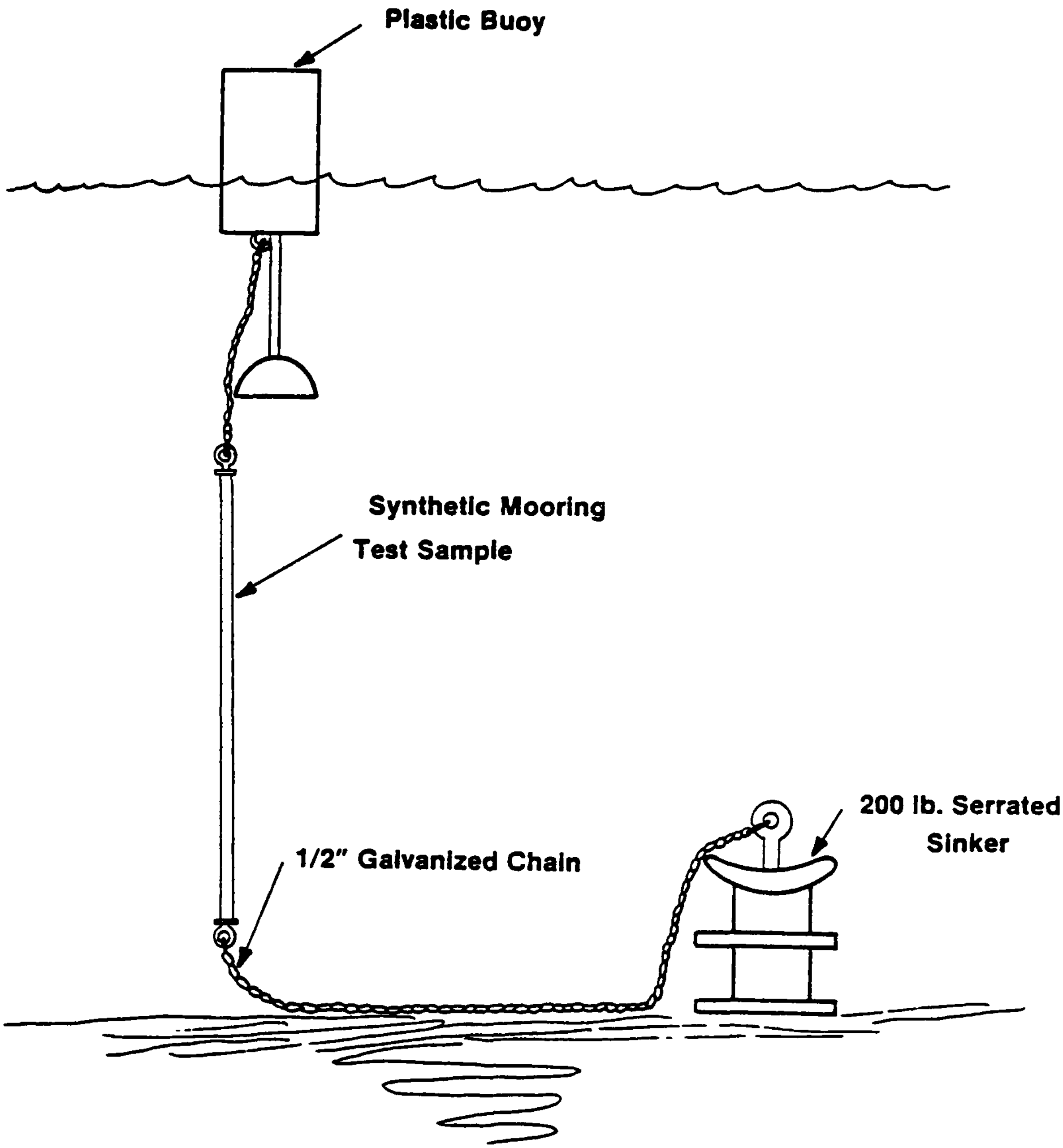

FIGURE G-1

Field Exposure Test Synthetic Mooring Configuration

FIGURE G-2
PLASTIC BUOY

c. Half-Inch Galvanized Chain. All moorings included forty feet of half-inch galvanized chain. In all cases, the chains were heavily corroded in the top five or ten feet. This corresponds to the approximate length of chain that was off the bottom. The section of chain that was on or in the bottom showed almost no corrosion. Figure G-3 showed both ends of the same chain. The reduced diameter at the top end had decreased the tensile strength to 950 to 3,000 pounds. Tensile strength of new galvanized chain is approximately 15,000 pounds. There were several cases where the chain pulled apart in the hands of a crewman while the buoy was being lifted aboard the workboat.

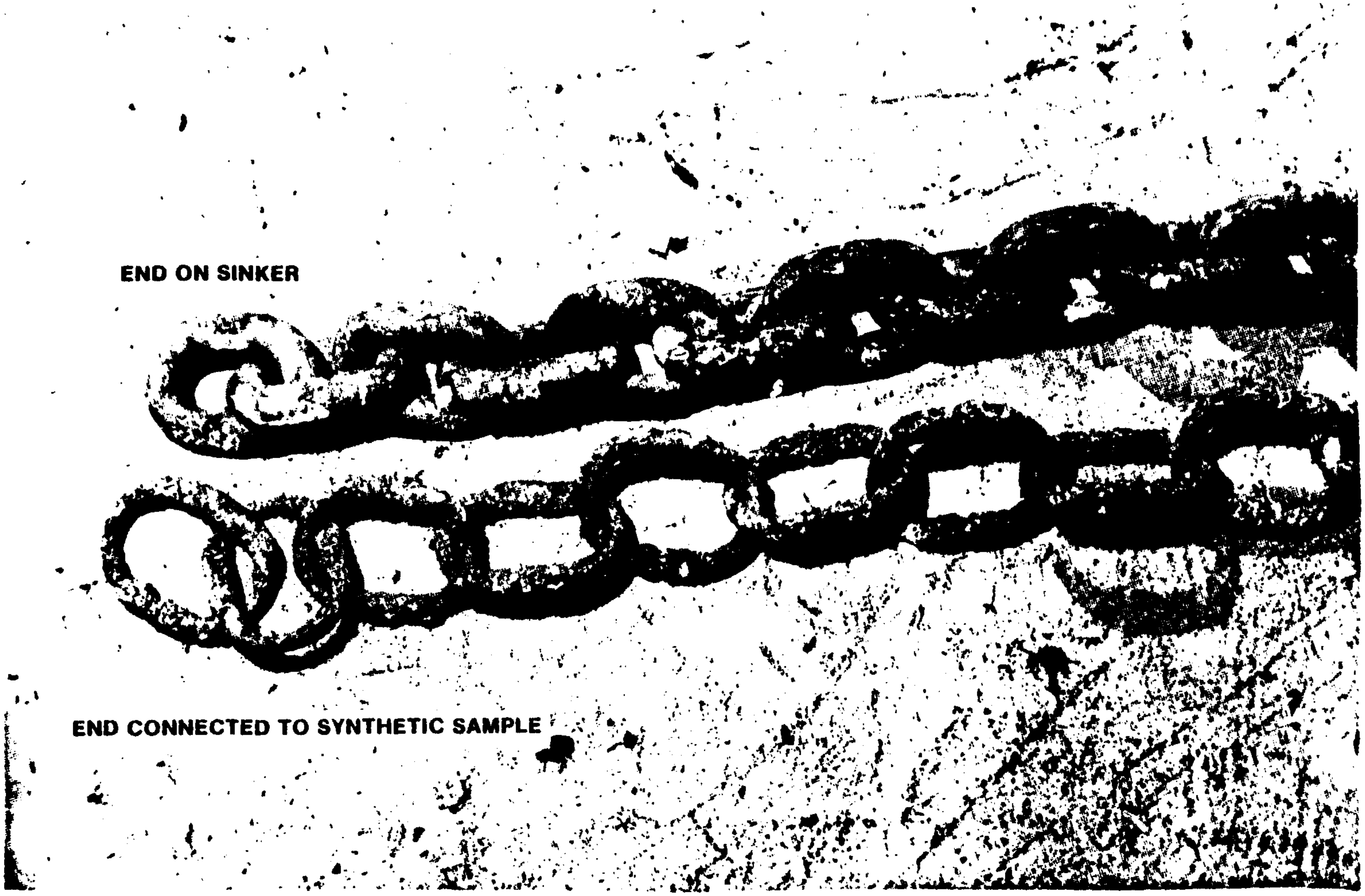

FIGURE G-3
1/2" GALVANIZED CHAIN

APPENDIX H

VISUAL INSPECTION OF SYNTHETIC MOORINGS AFTER FIVE YEARS OF DEPLOYMENT

The field exposure test mooring samples (section 4.3) were recovered and inspected carefully for damage and potential damage from marine growth. All samples were covered with various types of leafy and stringy algae (figure H-1). The growth in the upper six feet was very thick although lighter growth occurred on the entire 20-foot sample. A large number of mussels were attached to the top part of the line also. There is no visual indication of damage from mussels because they attach themselves to and hang from the line by byress threads. These threads do not appear to damage the line. Several samples had one or two pulled yarns; however, this had no apparent effect on tensile strength because failure did not occur at those points when tensile tested. Small mussels were attached to the line inside the thimble but the line was not damaged. All samples were stored in water from the time they were recovered until they were tested. Dynamic tests were conducted with the samples submerged in water also.

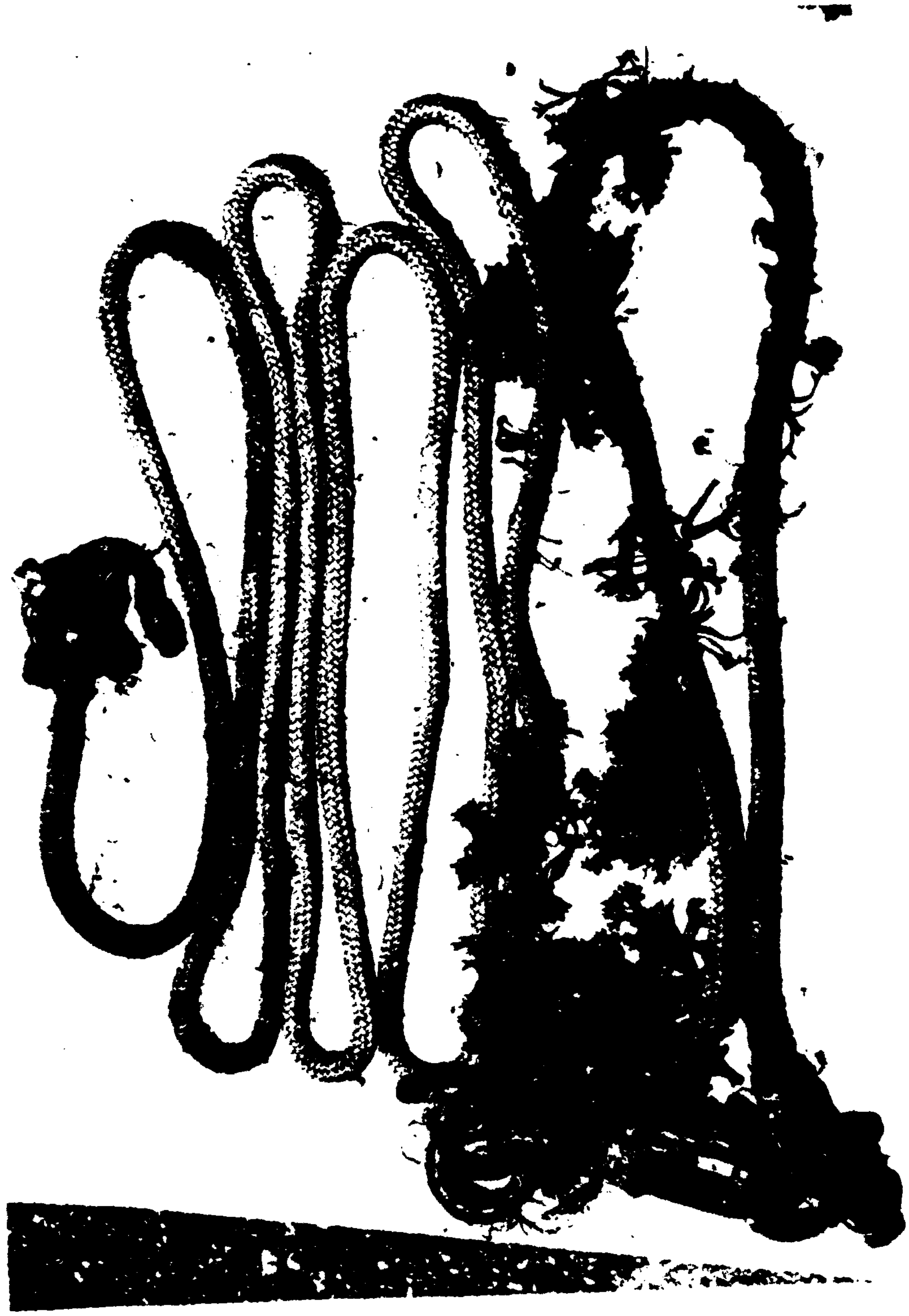

FIGURE H-1 (a)

FIGURE H-1 (b)

FIGURE H-1 (c)